ENERGY LOSS OF HIGH ENERGY ELECTRONS IN ALUMINUM, COPPER, AND LEAD

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THESIS

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June 1969

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ABSTRACT

The energy distributions of electrons of about 54, 75, and 92 MeV were measured before and after passing through lead absorbers of thicknesses ranging from 0.706 to 2.825 gm/cm^2, and through copper and aluminum absorbers up to 5.726 gm/cm^2. The electrons were accelerated by the LINAC of the Naval Postgraduate School. A measurement to determine the optimum location of the absorber indicated that the separation between the scattering foil and absorber should not exceed 6 cm, if geometric difficulties are to be avoided. The most probable energy losses agree with the theory of Blunck and Westphal for all three materials and all thicknesses. The half-widths of the distributions agree with theory up to thicknesses of about 2 gm/cm^2. For greater thicknesses the experimental half-widths of copper absorbers appear to agree with theory; the experimental half-widths of aluminum are greater than theoretical predictions; and those of lead are smaller than theory predicts.

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I. INTRODUCTION

The energy distribution of an initially monoenergetic electron beam which has passed through a layer of matter has been calculated by Blunck and Westphal [1]. This calculation evolved from the earlier theoretical work of Landau [2], Eygers[3], Bethe and Heitler [4], and Blunck and Leisegang[5]. It essentially accounts for the energy loss distribution due both to ionization and excitation and to radiation. The theory is based on the assumption that the absorbing material is sufficiently thin so that the energy loss is small compared to the initial energy of the electrons. The development of the theory is contained in Section II.

A number of experiments to measure the energy loss distribution of high energy electrons in thin layers of various materials have been performed, with incident energies in the range 10 MeV to 150 MeV. Of particular interest are the works of Breuer on aluminum at the Darmstadt linear accelerator [6]; Bumiller, Buskirk, Dyer, and Miller on aluminum at the LINAC of the Naval Postgraduate School [12,16], and Goodwin on copper, also at the Naval Postgraduate School [13]. The experimental works listed above are generally consistent in their results.

In each case agreement was found between experiment and theory for thin absorbers (< 2.0 gm/cm^2). However, for thicker layers of material the theory fails to predict the energy distribution experimentally realized. It is not clear how rapidly the theory breaks down as the energy loss becomes significantly large compared to incident energy.

In this thesis data are presented for the energy loss distribution in lead for absorber thicknesses from 0.706 to 2.825 gm/cm^2. Additional data were obtained for thick layers of aluminum and copper to supplement the experimental results obtained by Bumiller et.al. [15] and Goodwin [13]. The energy losses ranged from 1% to about 17% of the incident beam energy. The energy loss distribution can be characterized by the most probable energy loss Q_p and the half-width, which is the energy width of the distribution curve measured at one-half the peak intensity. These values are used to compare experimental results with theoretical predictions, as well as to compare with other work.

II. THEORETICAL CONSIDERATIONS

The Blunck and Westphal theory of the distribution for the energy loss suffered by an initially monoenergetic beam of electrons in passing through a layer of absorbing material assumes that the energy loss Q is small compared to the initial energy, E_i. Let W(Q)dQ be the probability of energy loss between Q and Q + dQ and x equal that amount of Q lost by radiation. Then the ionization loss equals (Q - x). This leads to the equation

$$W(Q)dQ = \int_o^Q W_I(Q - x)W_s(x)dxdQ \qquad (1)$$

where W_I and W_s are the energy loss distributions for ionization and radiation, respectively.

For the distribution of energy loss due to ionization and excitation, W_I, the Landau equation [2], as modified by Blunck and Leisegang, is used. The distribution is expressed as a function of the dimensionless parameter λ:

$$W_I(Q)dQ = \Phi(\lambda)d\lambda = \sum_n \frac{c_n\gamma_n}{\sqrt{b^2 + \gamma_n^2}} \exp\left[-\frac{(\lambda - \lambda_n)^2}{(b^2 + \gamma_n^2)}\right] d\lambda \qquad (2)$$

where

$$\lambda = \frac{Q - \bar{Q}}{aR} + \ell n\left(\frac{E_i}{aR}\right) - 1.116 \qquad (3)$$

The quantities introduced above are defined as follows: c_n, γ_n, and λ_n are constants used by Blunck and Leisegang to fit the Landau distribution to a sum of Gaussian functions. Their values are listed in Ref. [5] R is the thickness of the absorber measured in cm.

The quantity a is a function of the atomic number Z, the atomic weight A and the density ρ of the material, and $\beta(= v/c)$ of the electrons:

$$a = \frac{0.154\ Z\rho}{A\ \beta^2} \qquad \frac{MeV}{cm} \tag{4}$$

The quantity b^2 is a correction to Landau theory given by Blunck and Leisegang [3]:

$$b^2 = \frac{3.0}{aR} \sum_m \frac{I_m N_m}{Z} \cdot \ell n \left[\frac{2E_i}{I_m(1 - \beta^2)} \right] \tag{5}$$

where the summation is made over the m ionization potentials of the atomic electrons of the material, while N_m is the number of electrons with ionization potential I_m. Blunck and Westphal [1] and Breuer [6] used the approximation

$$b^2 = 2 \times 10^{-5} \frac{\bar{Q} Z^{4/3}}{(aR)^2} \tag{6}$$

This approximation is valid for aluminum and was used in making the theoretical calculations so as to permit comparison with previous experiments. However, the calculations for copper and lead were made using eq. (5).

$\bar{Q}$ is the average energy loss due to ionization (no radiation) for electrons of incident energy E_i, and is given below.

As can be seen from eq. (3), λ depends directly on $\bar{Q}$. Thus the width and most probable energy loss corresponding to the distribution $\Phi(\lambda)$ depend on $\bar{Q}$. Sternheimer [7,8,9] has calculated this quantity as follows:

$$\bar{Q} = \frac{A_s t}{\beta^2} \left[B + 0.43 + \ell n\ E_i - \beta^2 - C - a_s (x_1 - \log_{10} \frac{P}{mc})^{m_s} \right] \text{ MeV} \tag{7}$$

where t is the thickness in gm/cm^2 and the constants As, B, C, X_1, a_s, and m_s are parameters of the material and listed in Ref. 9. The most probable energy loss due to ionization and excitation (without radiation) is given by:

$$Q_p = \frac{A_s t}{\beta^2}\left[B + 1.06 + \ell n\left(\frac{A_s t}{\beta^2}\right) - \beta^2 - C - a_s\left(X_1 - \log_{10}\frac{P}{mc}\right)^{m_s}\right] \text{MeV} \quad (8)$$

For W_s, the distribution of energy loss due to radiation, Blunck and Westphal give [3,4]:

$$W_s(Q)dQ = B\alpha R\left(\frac{Q}{E_i}\right)^{\alpha R}\frac{dQ}{Q} \quad (9)$$

where

$$\alpha = 1.40 \times 10^{-3}\frac{\rho Z^2}{A}\left[\frac{4}{3}\ell n\left(\frac{183}{Z^{1/3}}\right) + 1/9\right] cm^{-1} \quad (10)$$

and B is a normalizing factor $= \frac{1}{\Gamma(\alpha R + 1)}$

The distribution of energy losses according to Blunck and Westphal is obtained by putting Eqs. (9) and (2) into eq. (1) and performing the integration. The results give an energy loss probability distribution for a single electron of incident energy E_i. For comparison between experimental results and theory this distribution function has been utilized, with corrections to account for the finite energy width of the incident electron beam. This treatment is described in Section IV.

III. EXPERIMENTAL PROCEDURE

The experimental arrangement used was similar to that described by Breuer [6], Miller [12], and Goodwin [13]. The LINAC of the Naval Postgraduate School was used to accelerate electrons to energies from 54 to 97 MeV. These electrons were elastically scattered at 90^{o} from a thin (0.076 mm) aluminum scattering foil, thence passing through the absorber, and finally energy-analyzed by a 120^{o} magnetic spectrometer described by Kenaston, Luke and Sones [11]. A figure of this arrangement is given in Refs. [12] and [13].

According to Miller [12], the results of energy loss experiments with aluminum appeared to be quite sensitive to geometrical considerations. In his work data were collected with the absorbing material positioned approximately 22 cm from the scattering foil. The results with this arrangement showed a general lack of agreement with theoretically predicted half-widths. Only when the absorber was placed approximately 3 cm from the scattering foil did the experimental half-widths show reasonable agreement with theoretical prediction and the results of Breuer [6].

Consequently, an experiment was conducted to determine the optimum positioning of the absorber with respect to the scattering foil. A device was fabricated whereby the absorber could be positioned at various distances from the scattering foil. For details of the experimental arrangement and a diagram of the apparatus, see Figs. 1 and 2. A portion of Miller's experiment was repeated, using an incident energy beam of 53.8 MeV and an aluminum absorber of thickness 1.441 gm/cm^2. The separation was varied from 3 to 20 cm and the energy distribution

measured. The results of these measurements as well as the theoretical prediction are shown in Fig. 3. It was determined that the separation had no effect on the location of the peak of the energy loss curve, but that the half-width increased as the distance increased. Agreement with theory as well as previous experimental data was attained for a radial separation < 6 cm. Thus in the remainder of this work the absorbing layers were positioned approximately 3 cm from the scattering foil.

Because the incident electron beam scattered into the absorbing material is not monoenergetic, the energy distribution of the electron beam was measured both before and after passing through the absorbing materials. Various thicknesses of each material were positioned into the beam by a remotely-controlled device. This enabled changing of absorber thickness without turning off the accelerator and thus possibly altering the character of the electron beam. The data represent the number of electrons detected by a coincidence counting system at the exit of the magnetic spectrometer. A downstream Secondary Emission Monitor was used as a standard for normalization purposes, in that each data point corresponds to a given predetermined integrated current. This corresponded to a certain number of electrons passing through the absorbing material.

IV. TREATMENT OF DATA

It was first necessary to correct all data taken for background, counting loss and accidentals. Background was measured by taking counts with the scattering foil removed from the path of the incoming beam and integrating to the appropriate current. Counting loss corrections were applied using the formula:

$$n_{corr} = n(1 + K\dot{n}) \tag{11}$$

where K is a characteristic constant of the counting system - in this case .003 - and $\dot{n}$ is the count rate. Accidental coincidence counts were measured by means of a 63 nsec delay line, and appropriately deducted. Because of low background and the counteracting characteristic of counting loss and accidental coincidences these corrections had negligible effect on the data.

Since the theory of Blunck and Westphal is based on a monoenergetic incident beam, the energy spread of the incident electrons must be taken into consideration. Such an energy spread will increase the half-width, and because of the asymmetry of the energy distribution will increase the most probable energy loss. To account for these effects the IBM 360/67 computer of the Naval Postgraduate School was used to unfold the measured incident energy distribution into the theory. The method is described in detail by Miller [12] and Goodwin [13]. For a computer program to accomplish this unfolding, see Appendix C.

In the comparison of the data with theory, the measured incident energy distribution was unfolded as described above, properly normalized to the experimental data and plotted. From these plots the

theoretical half-widths and most probable energy losses were extracted. The experimental data were superimposed on the theoretical curves and the measurable parameters compared. The results for various incident energies, absorber materials, and thicknesses are shown in Fig. 4 through 23. The solid lines represent the theoretical energy distributions, while the crosses indicate experimental data points. To avoid clutter on the figures approximately 25% of the data points have been omitted. A representative sampling of error bars is included.

V. RESULTS AND OBSERVATIONS

The theoretically predicted and experimentally measured values of half-widths and most probable energy losses for the various incident energies, absorber materials, and thicknesses are shown in Tables I, II, and III. In addition to the experimental data and the Blunck and Westphal predictions, the theoretical value of the most probable energy loss due to ionization, S, is listed for comparative purposes. The data for an incident energy of approximately 75 MeV for all three materials of various thicknesses are plotted in Figs. 24 and 25.

For the thickest lead absorber ($t = 2.825$ gm/cm^2) at 91.37 MeV and the copper ($t = 5.726$ gm/cm^2) at 53.63 MeV a half-width was not obtained because of the shape of the low energy tail. In an attempt to get a half-width the energy spectrum of the electrons was examined down to about 5 MeV, the lower limit of reliability of the magnetic spectrometer. It was found that for thick absorbers secondary effects (probably due to shower production) cause a secondary peak of low energy electrons. This rise began in the vicinity of 30 MeV and peaked at about 15 MeV, approximately independent of incident energy and absorber material. It was noted that the amplitude increased with target thickness, and in the case of the thickest absorbers was as much as ten times greater than the primary peak. Measurement of the presence of positrons was made by reversing the polarity of the magnetic spectrometer. The energy spectrum of the positrons at low energy followed that of the electrons, but the intensity was much lower. This indicated that the lower energy tail was due in part to pair production resulting from the interaction of bremstrahlung with the absorber material, inasmuch as only a negligible number of positrons were

detected when the absorber was removed. Another possible contribution of electrons to the low energy tail is electron-electron scattering.

From Table I it may be seen that for lead the experimental results show agreement with theory in the most probable energy loss for all energies and thicknesses up to 2.825 gm/cm^2. There is agreement in the half-width for thicknesses up to 2.118 gms/cm^2, but at greater thickness the experimental half-width is smaller than that predicted by theory. This is in contrast with previous works with materials of lower Z where for thick absorbers the experimental half-widths are systematically greater than theory predicts.

Table II indicates that for a 5.574 gm/cm^2 aluminum absorber the most probable energy loss data agrees with theory within the error limits of the experiment. However, at an incident energy of both 53.44 and 74.47 MeV the experimental half-width is significantly greater than theory predicts.

For copper, again agreement between experimental data and theory for the most probable energy loss was observed up to 5.726 gm/cm^2. There appears to be agreement in the half-width for a thickness of 4.295 gm/cm^2, but the results of the experiments using the 5.726 gm/cm^2 absorber are inconclusive owing to the large degree of uncertainty.

It would appear in general that the Blunck and Westphal theory for the energy loss distribution of electrons is valid for predicting the most probable energy loss for aluminum, copper, and lead for incident energies in the range 54 to 97MeV. The theoretical prediction of half-width for thick absorbers seems best for copper, but perhaps is systematically too large for materials of higher Z and too small for those of lower Z.

In light of the foregoing further work is justified with materials of low and intermediate atomic number. Furthermore, a closer examination of the characteristics of the low energy tail and secondary peak is warranted.

APPENDIX A

TABLES

TABLE I. Energy Loss Distribution Characteristics of Lead

		Q_p(MeV)			HW(MeV)	
E_i(MeV)	t(gm/cm^2)	B&W	S	Experiment	B&W Folded	Experiment
53.85	0.706	0.83	0.69	0.81 ± .05	0.61	0.60 ± .06
	1.412	1.41	1.43	1.45 ± .08	1.21	1.23 ± .12
	2.118	2.65	2.20	2.64 ± .10	2.51	2.65 ± .25
	2.825	3.75	2.98	3.73 ± .15	7.44	3.00 ± .30
74.74	0.706	0.85	0.69	0.82 ± .05	0.83	0.82 ± .05
	1.412	1.80	1.45	1.80 ± .10	1.40	1.47 ± .07
	2.118	2.70	2.22	2.59 ± .12	2.50	2.24 ± .19
	2.825	3.90	3.01	3.80 ± .20	8.78	6.03 ± 1.0
91.37	0.706	0.92	0.70	0.87 ± .07	0.89	0.78 ± .08
	1.412	1.84	1.45	1.77 ± .10	1.54	1.52 ± .19
	2.118	2.84	2.23	2.75 ± .15	2.85	2.74 ± .64
	2.825	4.04	3.02	3.88 ± .20	*	*

* No half-width obtained.

TABLE II. Energy Loss Distribution Characteristics of Aluminum

		Q_p (MeV)			HW (MeV)	
E_i (MeV)	t (gm/cm^2)	B&W	S	Experiment	B&W Folded	Experiment
53.44	5.574	9.22	8.41	9.24 ± .13	3.65	4.60 ± .30
74.47	5.574	9.13	8.43	9.33 ± .25	4.00	5.7 ± 1.2

TABLE III. Energy Loss Distribution Characteristics of Copper

		Q_p (MeV)			HW (MeV)	
E_i (MeV)	t (gm/cm^2)	B&W	S	Experiment	B&W Folded	Experiment
53.63	4.295	6.28	5.56	6.23 ± .13	4.30	4.25 ± 1.20
	5.726	8.90	7.52	8.83 ± .20	*	*
76.02	4.295	6.29	5.57	6.28 ± .13	4.59	4.55 ± .50
	5.726	9.13	7.54	8.38 ± .25	9.20	10.1 ± 2.0
94.07	4.295	6.30	5.58	6.40 ± .20	4.61	~ 4
96.66	5.726	9.30	7.55	9.2 ± .5	15.55	16.4 ± 4.2

*No half-width obtained.

APPENDIX B

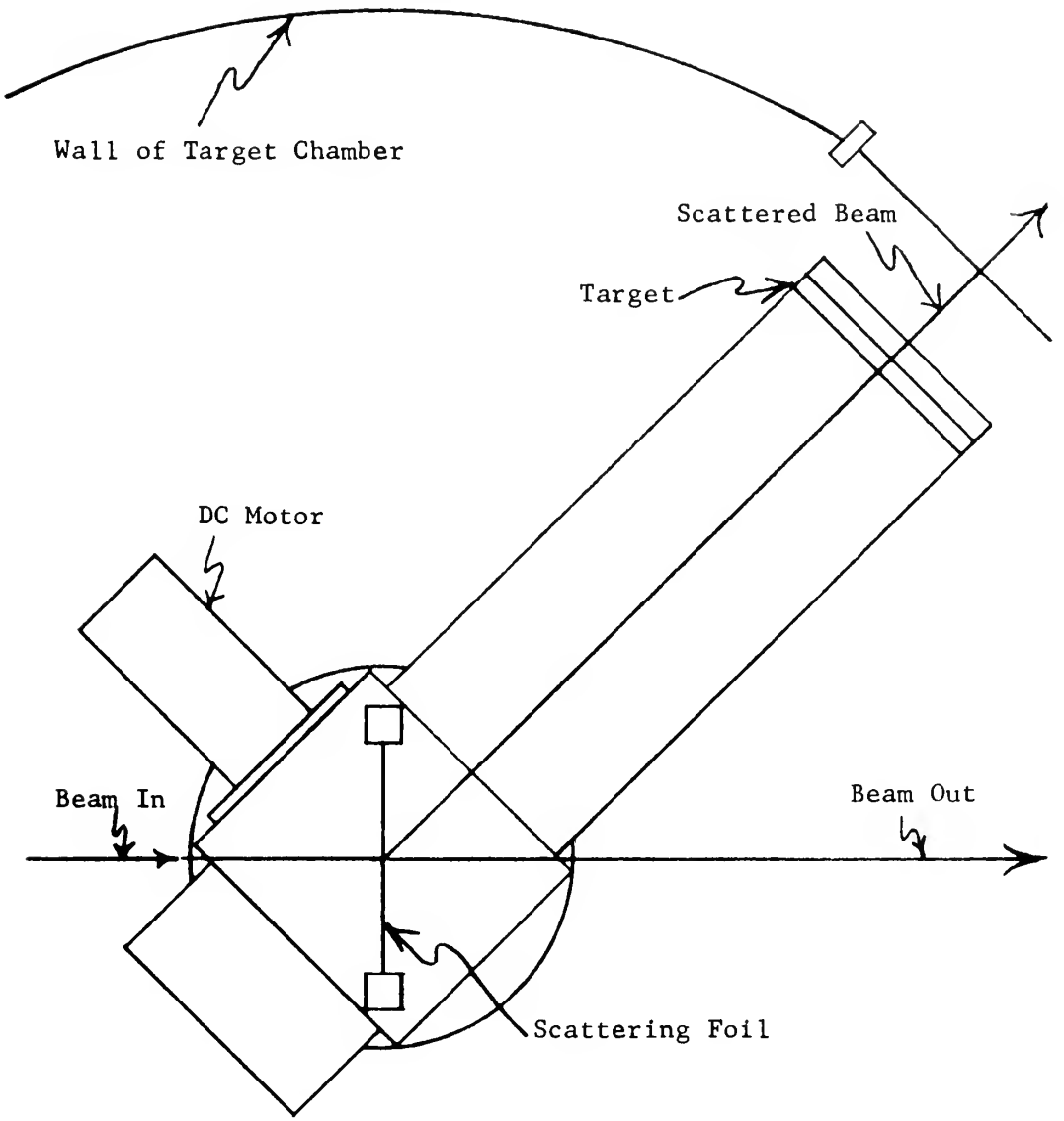

FIGURE 1. **Experimental Arrangement for Varying Foil-to-Absorber Distance in Beam Line.**

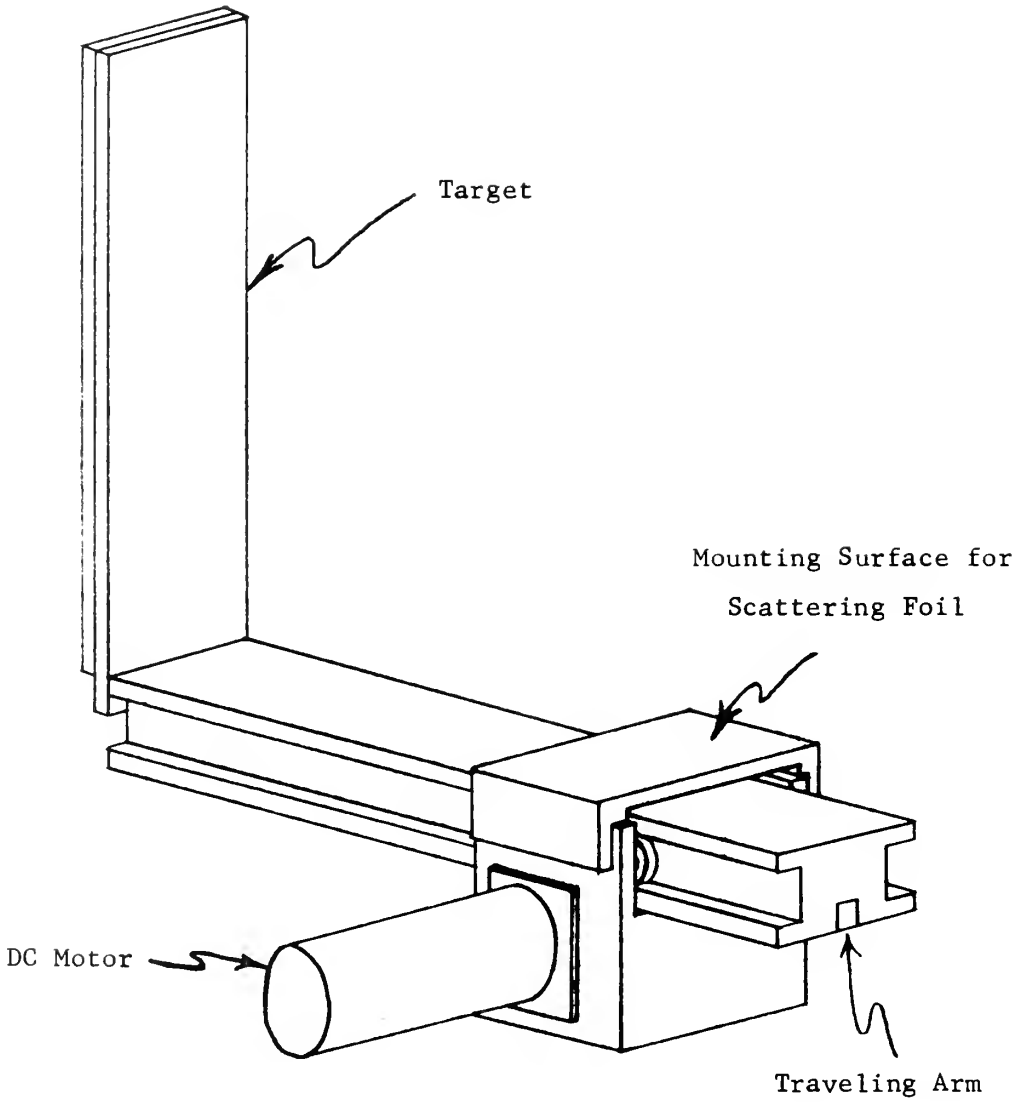

FIGURE 2. Device to Vary Radial Distance

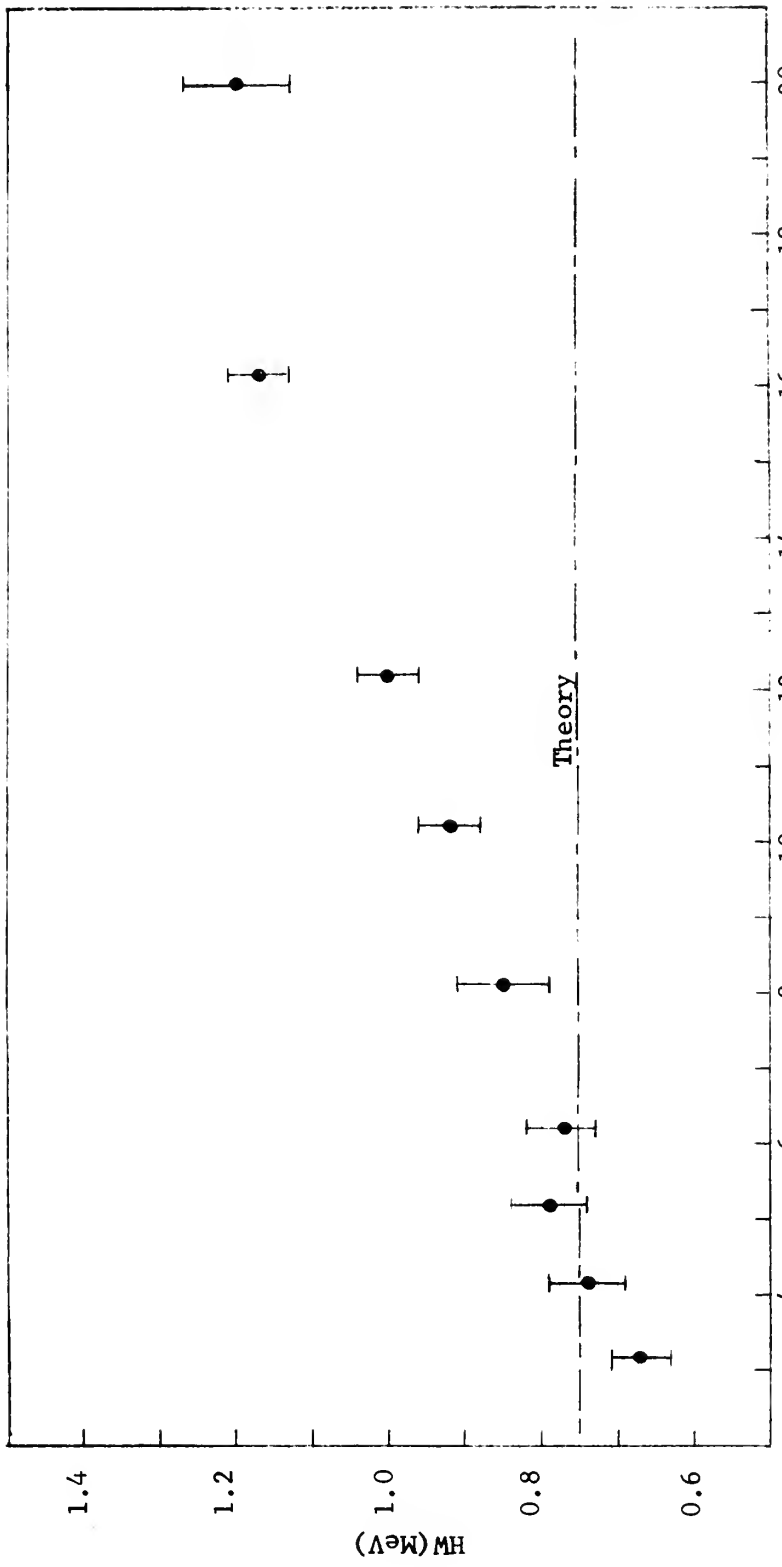

FIGURE 3. Half-Width of 1.441 gm/cm^2 Al Absorber vs Radial Distance

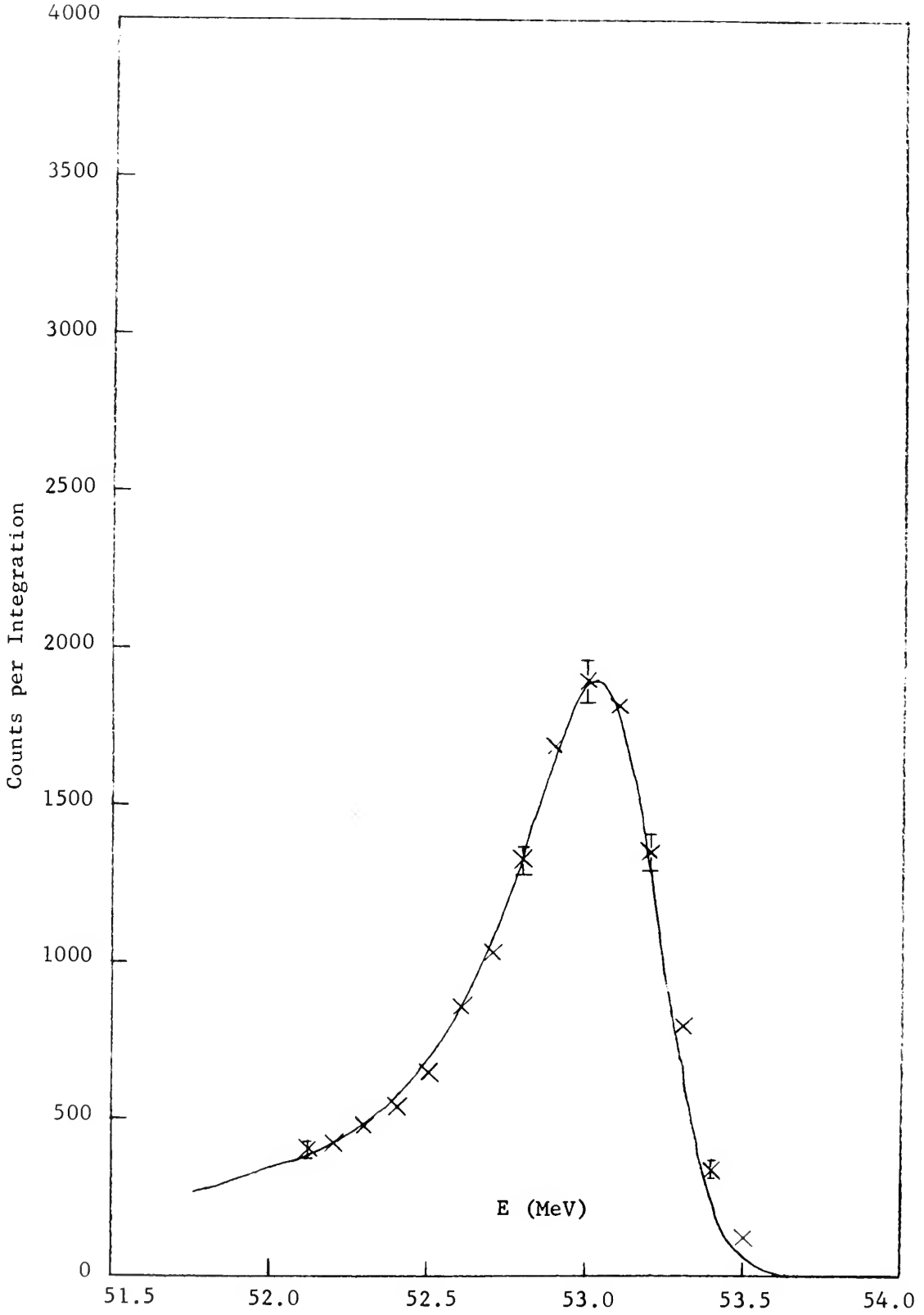

FIGURE 4. Pb, E_i = 53.85 MeV, t = 0.706 gm/cm^2

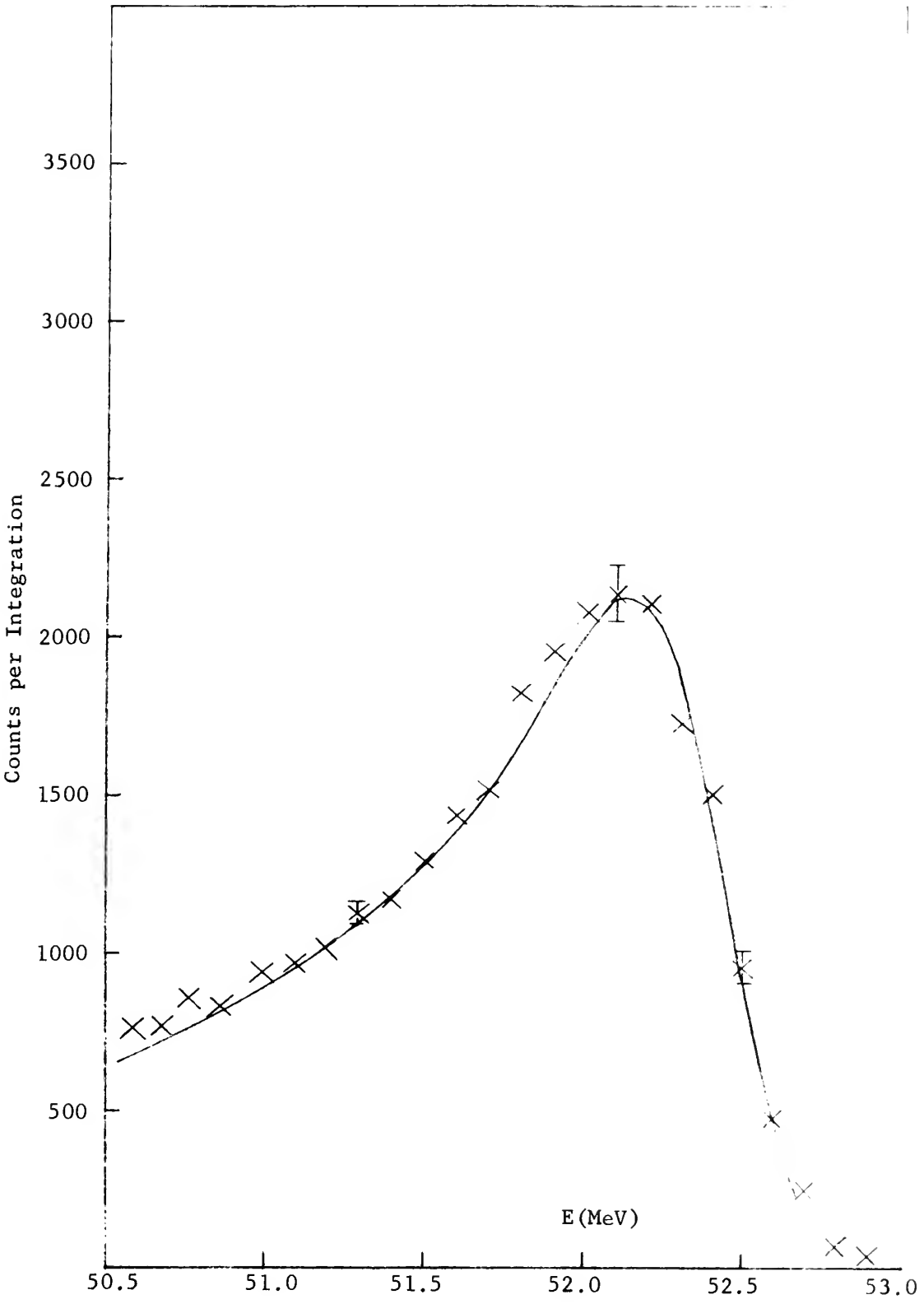

FIGURE 5. Pb, E_i = 53.85 MeV, t = 1.412 gm/cm^2

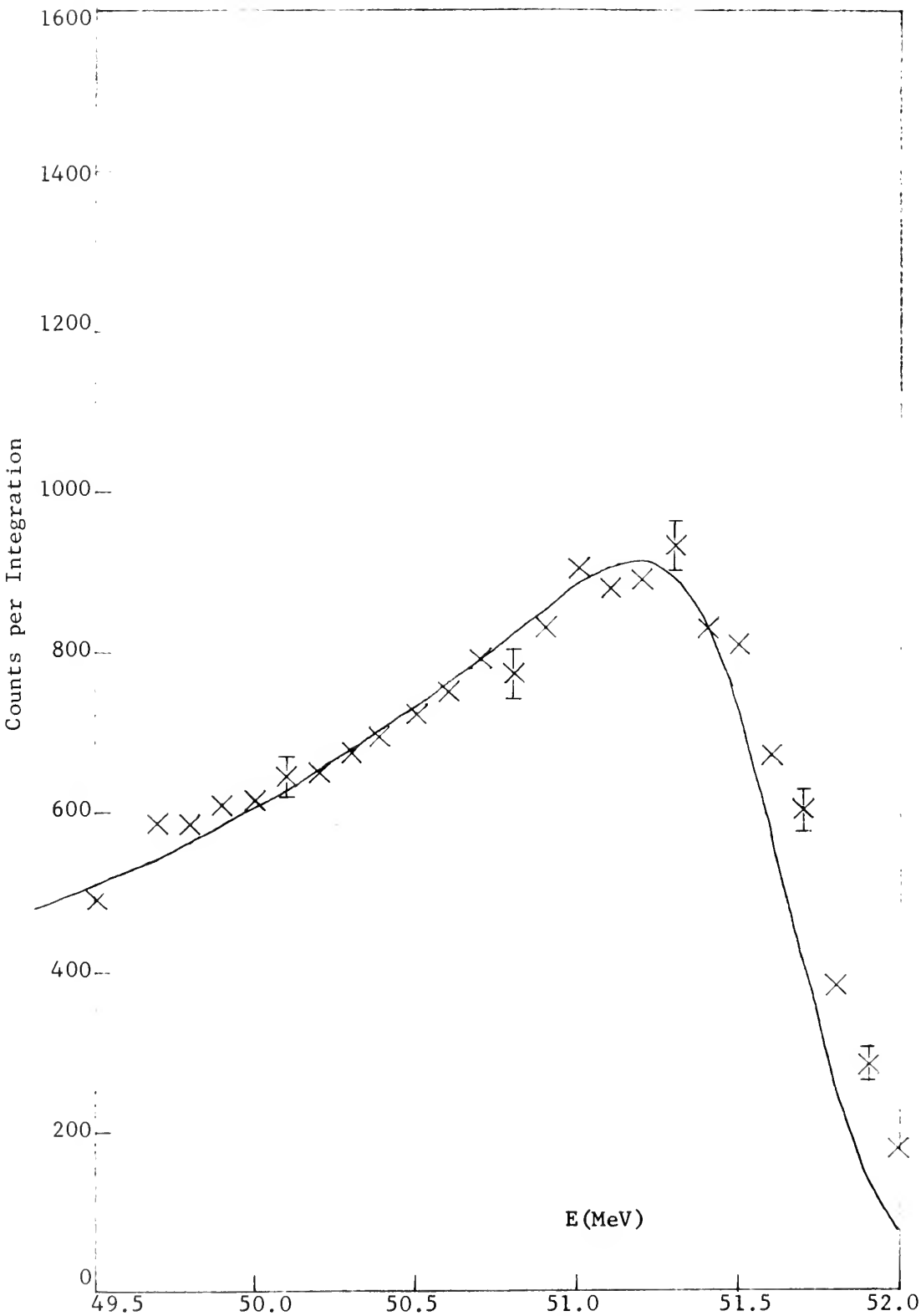

FIGURE 6. Pb, E_i = 53.85 MeV, t = 2.118 gm/cm^2

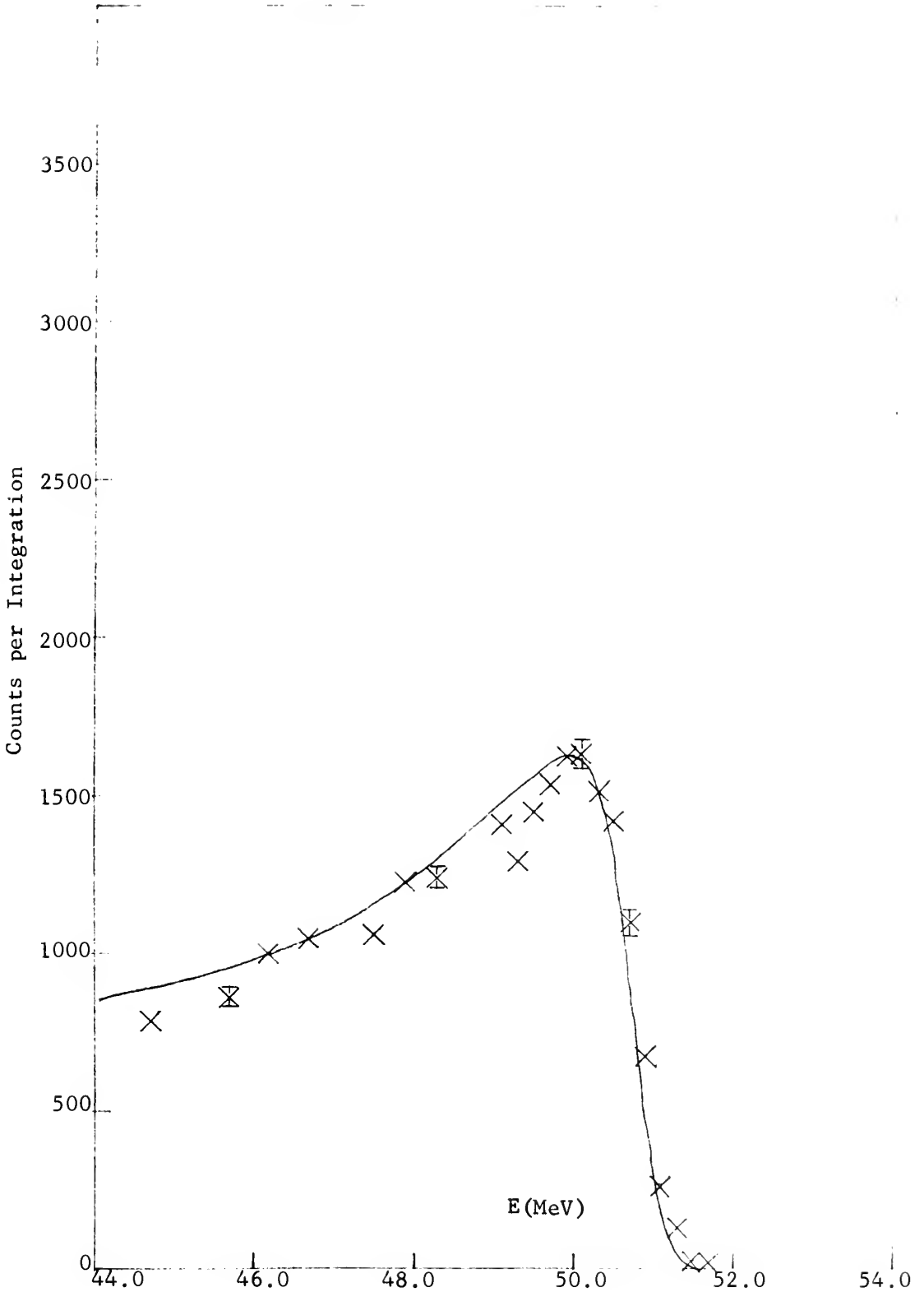

FIGURE 7. Pb, E_i = 53.85 MeV, t = 2.825 gm/cm^2

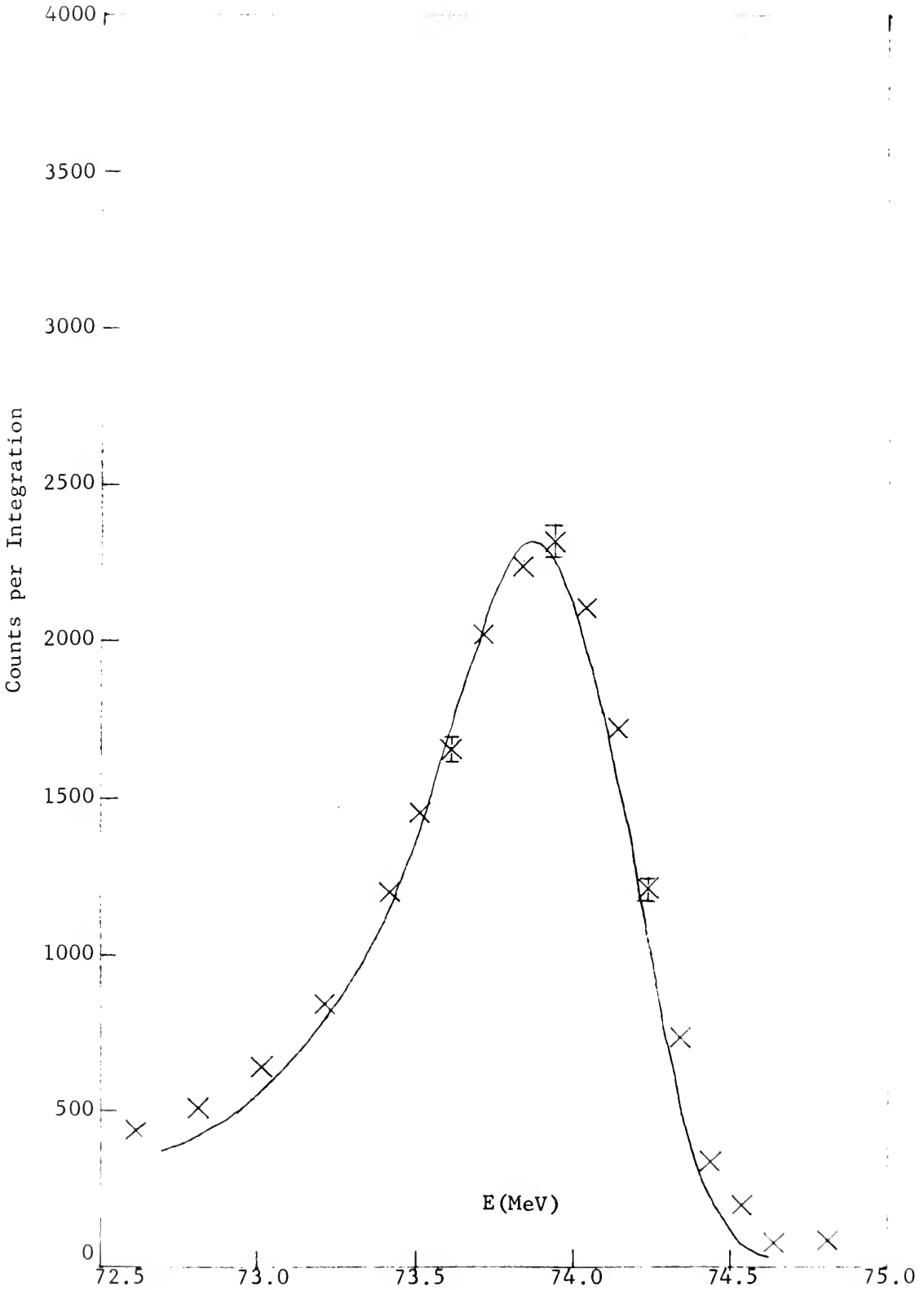

FIGURE 8. Pb, E_i = 74.74 MeV, t = 0.706 gm/cm^2

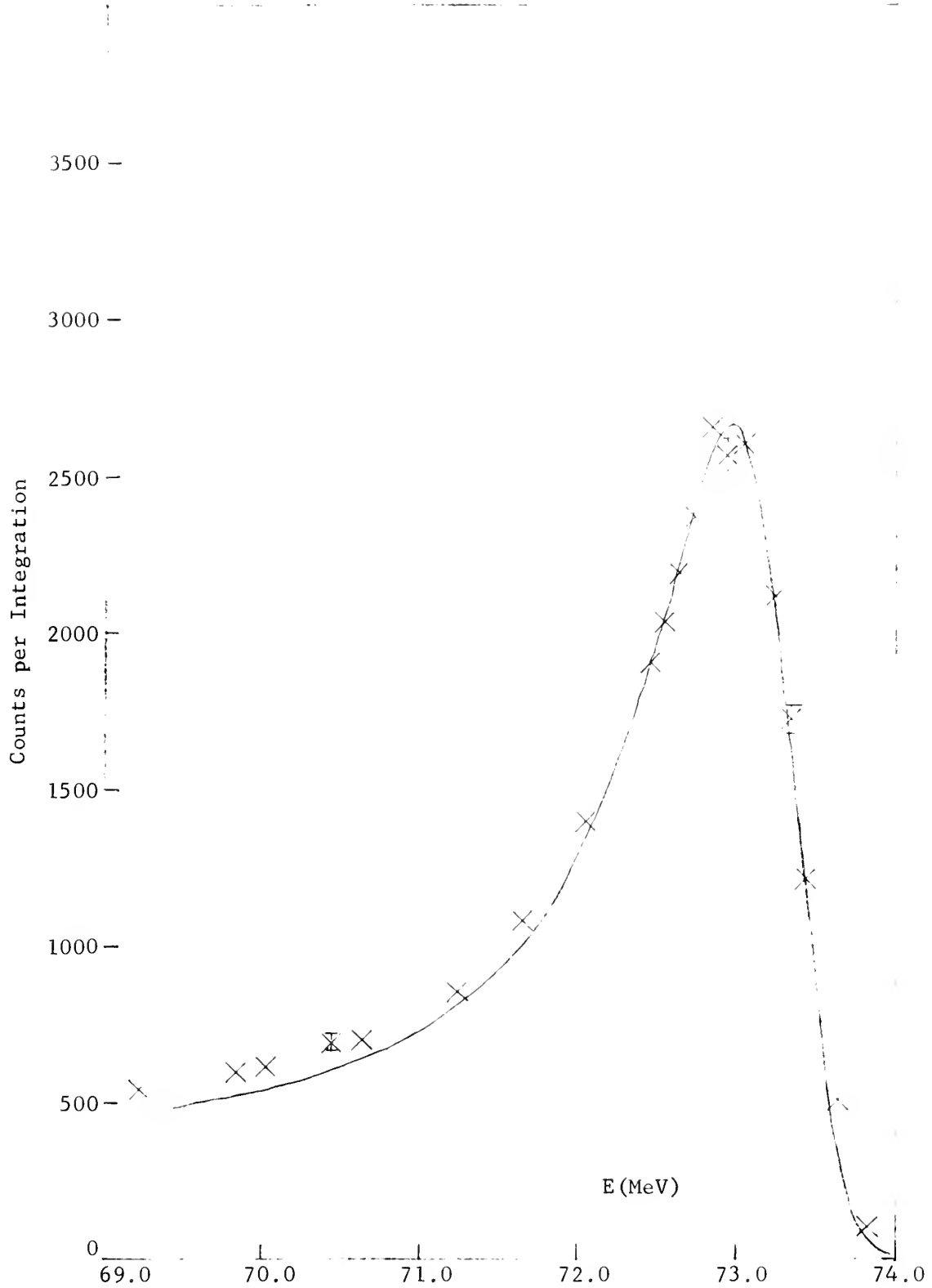

FIGURE 9. Pb, E_i = 74.74 MeV, t = 1.412 gm/cm^2

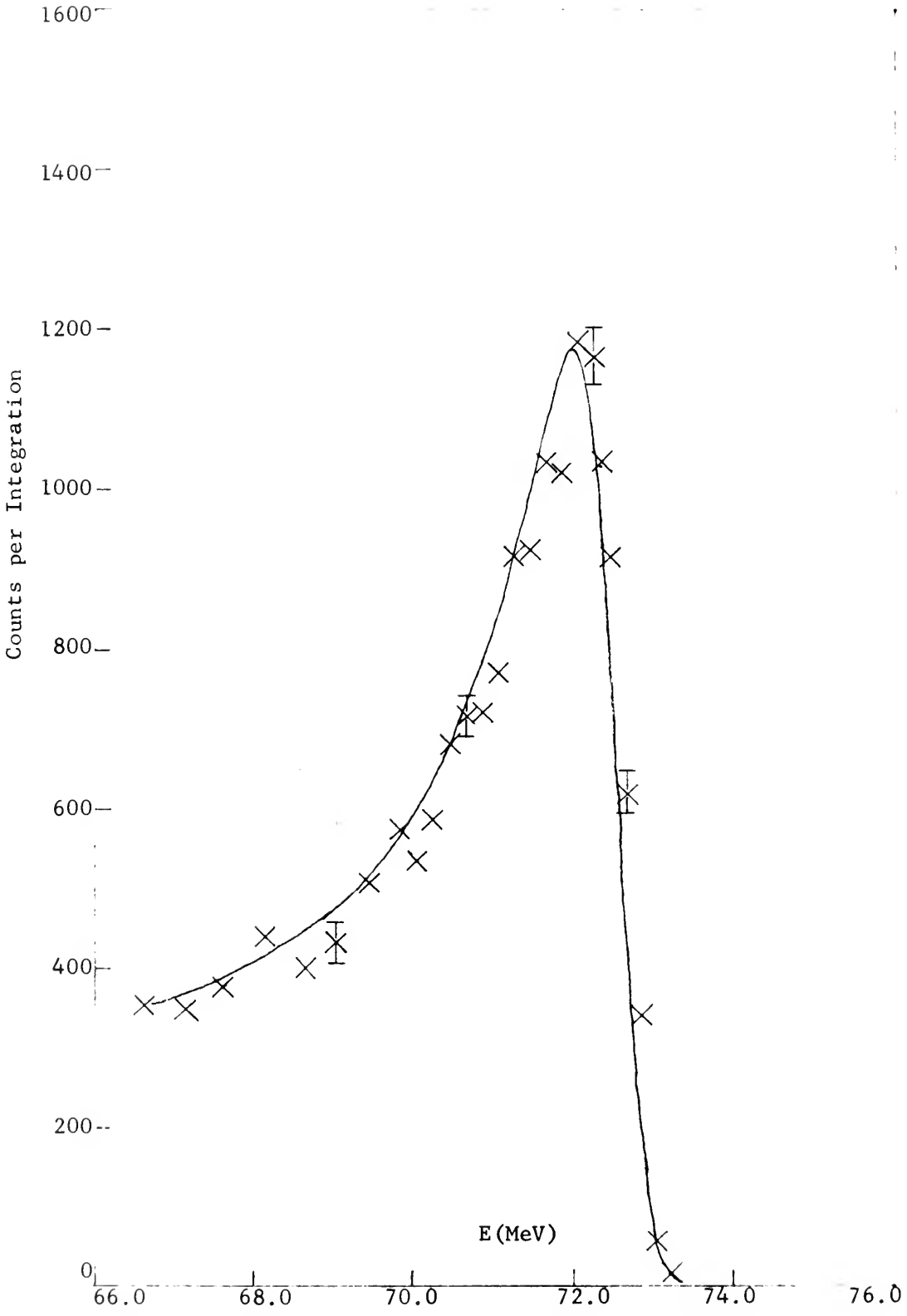

FIGURE 10. Pb, E_i = 74.74 MeV, t = 2.118 gm/cm^2

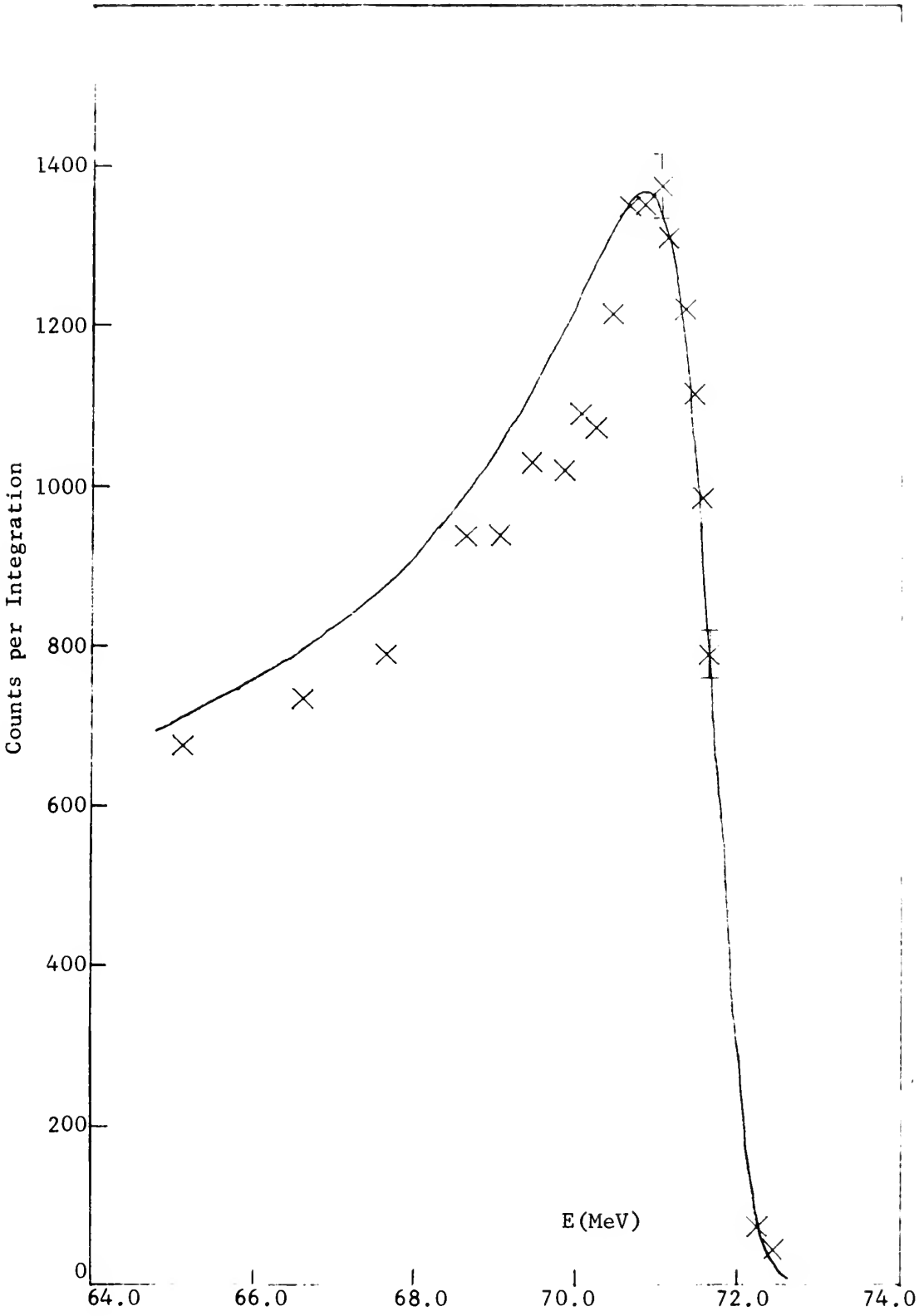

FIGURE 11. Pb, E_i = 74.74, t = 2.825 gm/cm^2

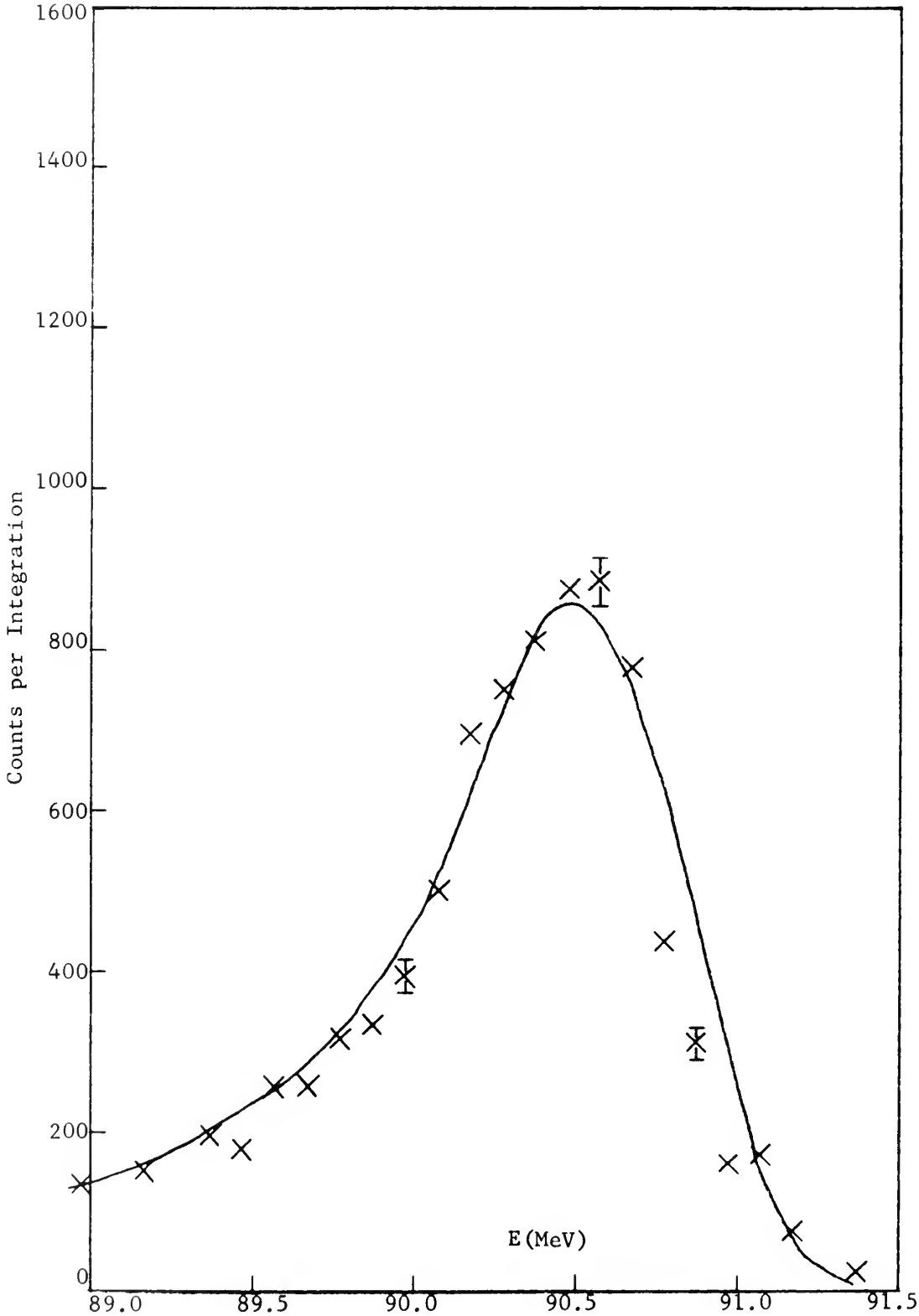

FIGURE 12. Pb, E_i = 91.37 MeV, t = 0.706 gm/cm^2

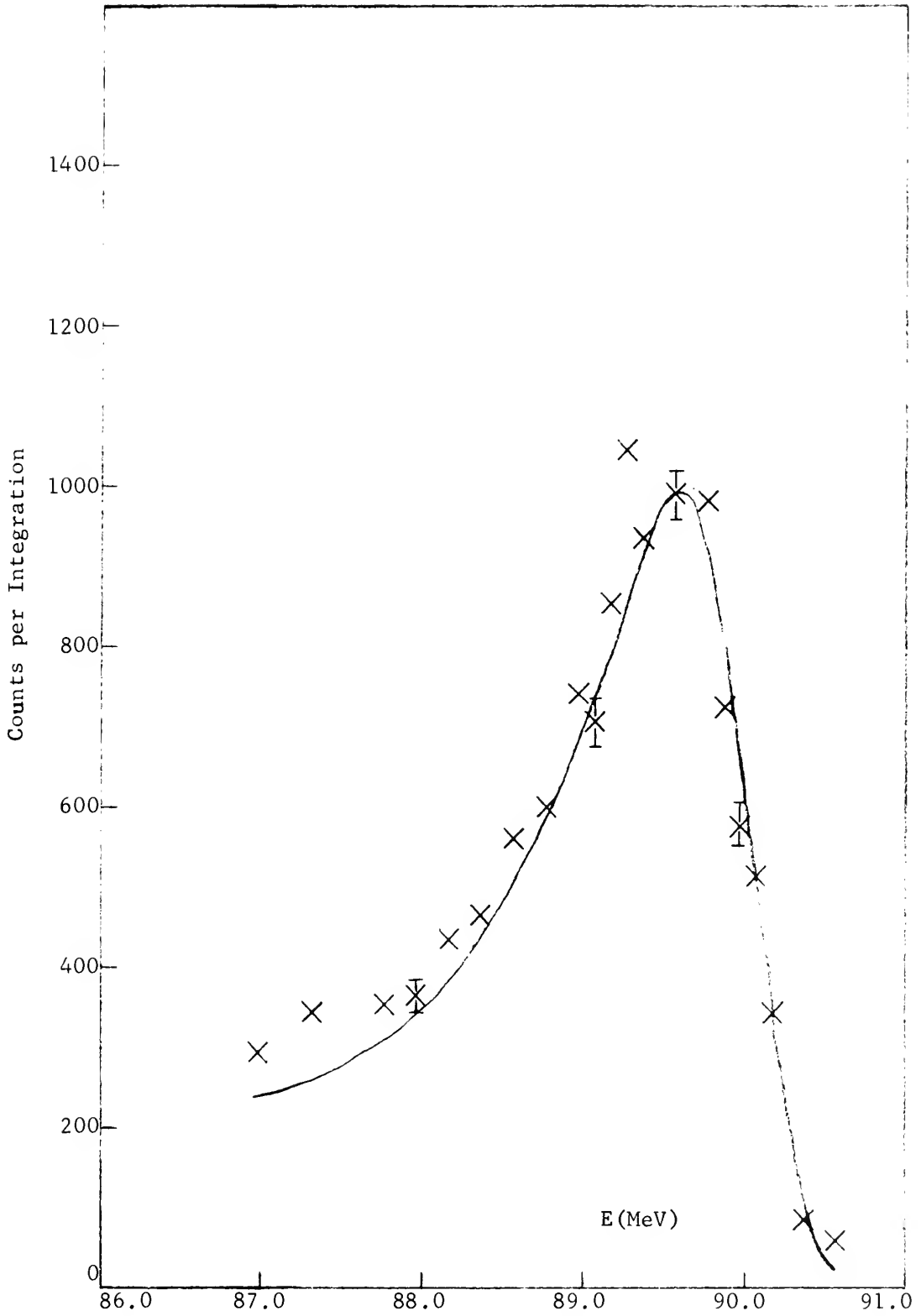

FIGURE 13. Pb, E_i = 91.37 MeV, t = 1.412 gm/cm^2

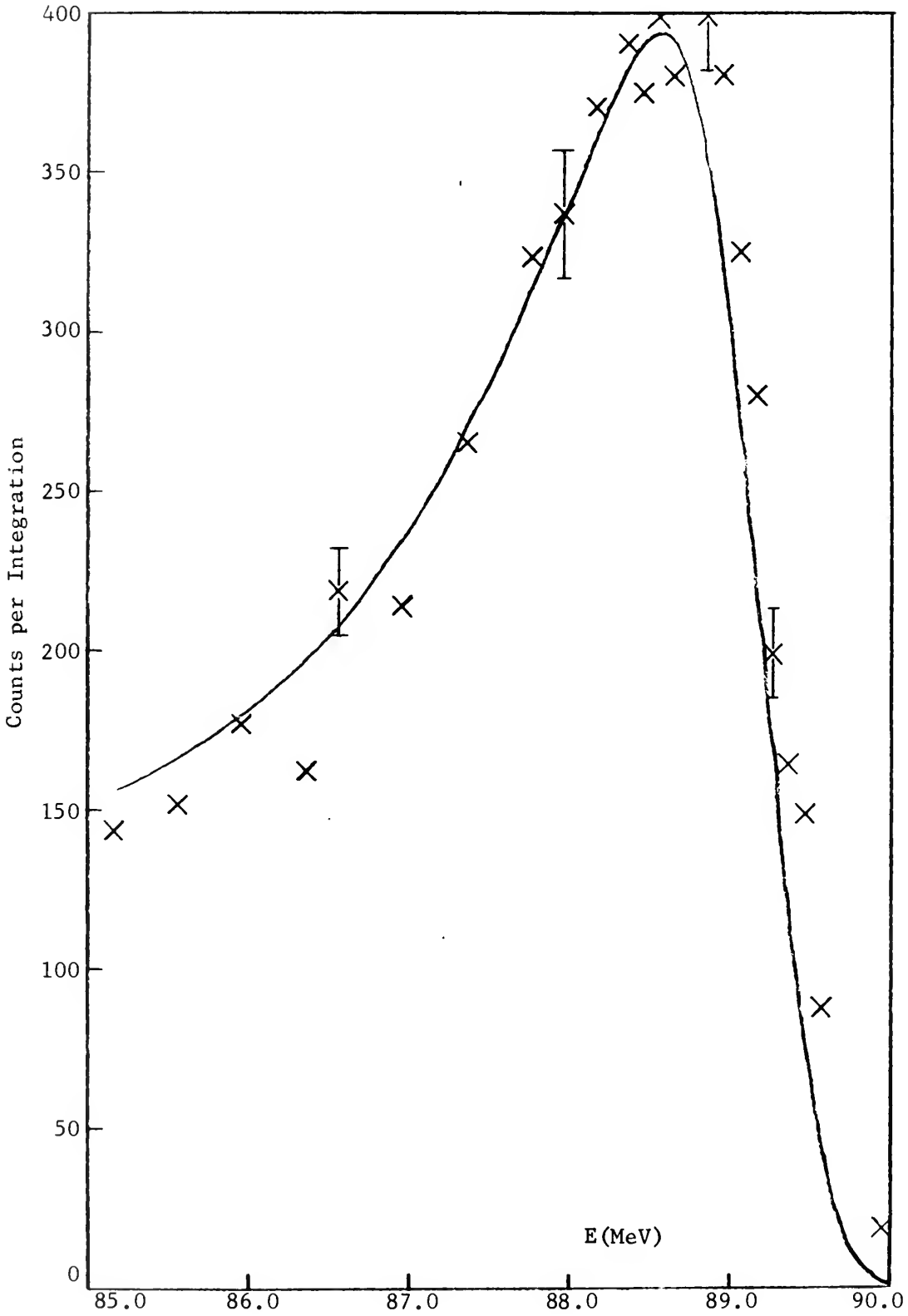

FIGURE 14. Pb, E_i = 91.37 MeV, t = 2.118 gm/cm^2

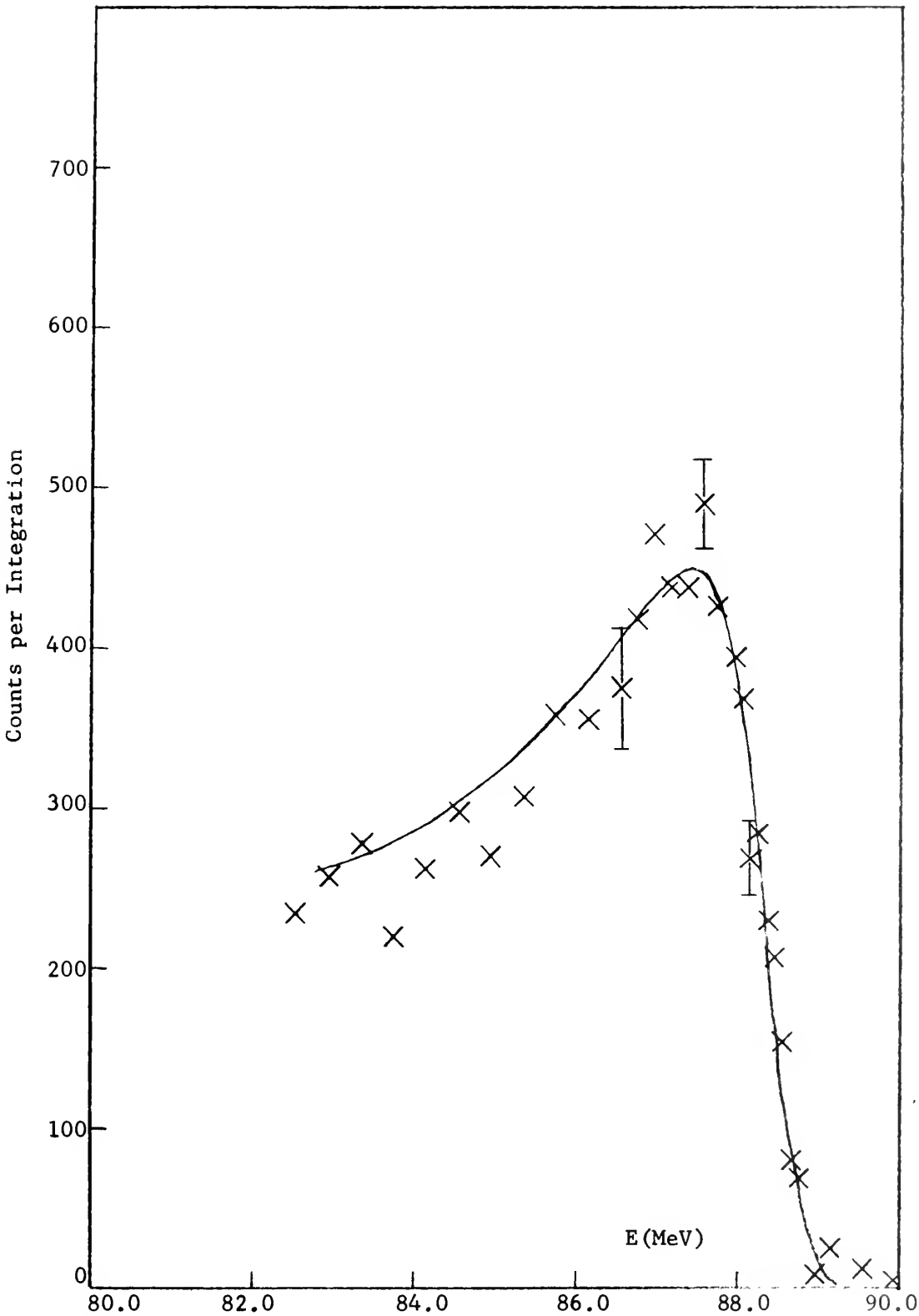

FIGURE 15. Pb, E_i = 91.37 MeV, t = 2.825 gm/cm^2

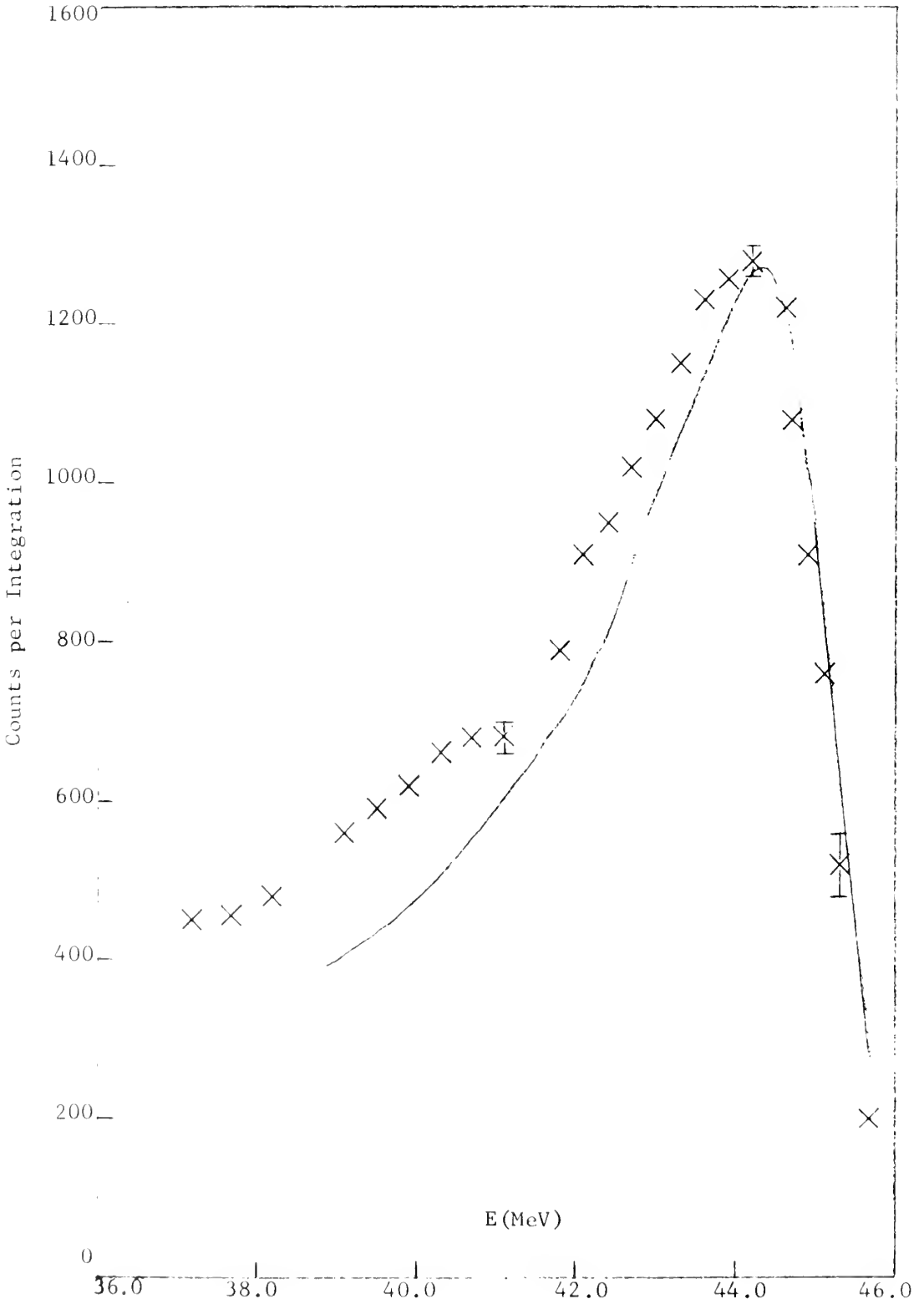

FIGURE 16. Al, E_i = 53.44 MeV, t = 5.574 gm/cm^2

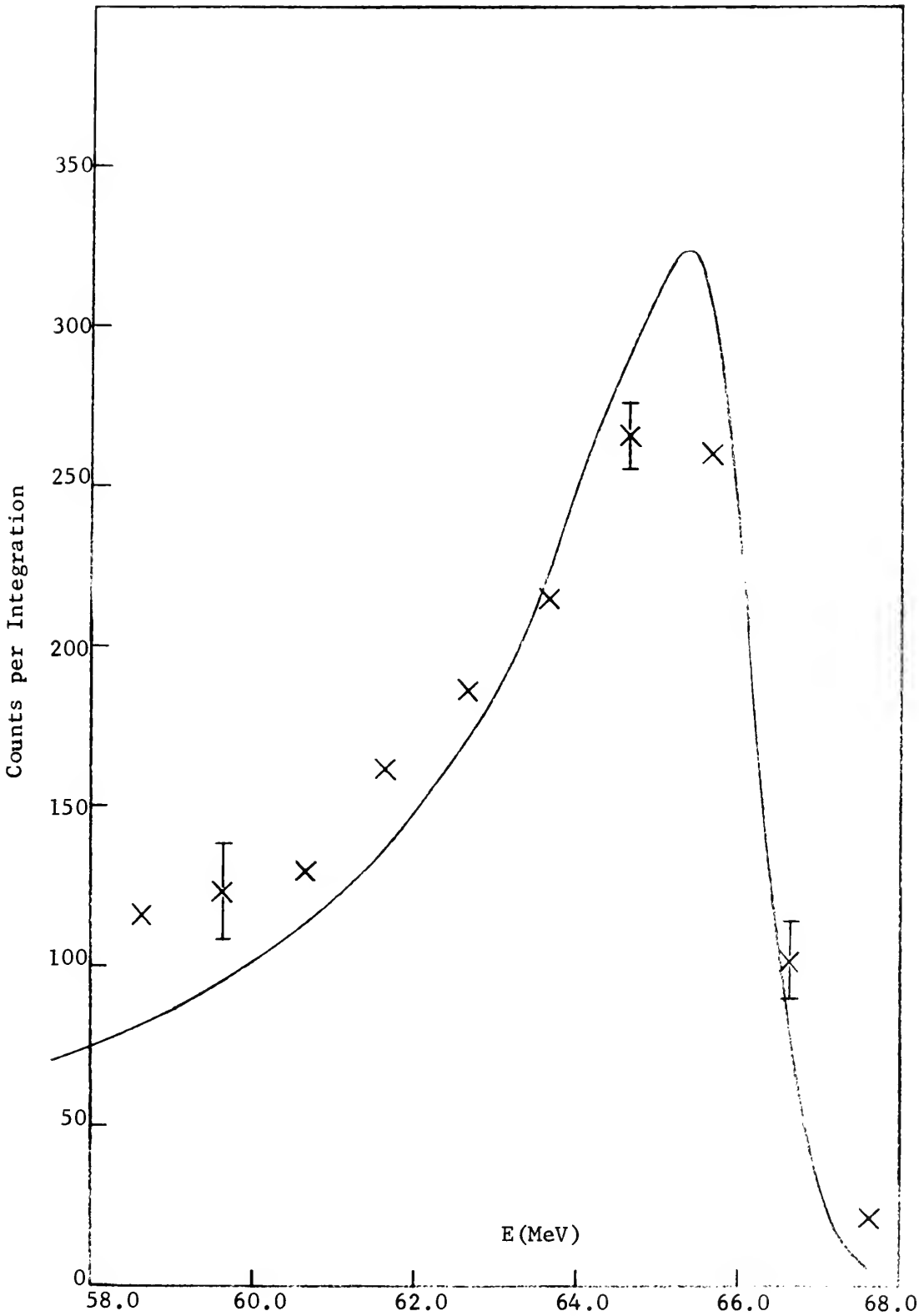

FIGURE 17. Al, E_i = 74.47 MeV, t = 5.574 gm/cm^2

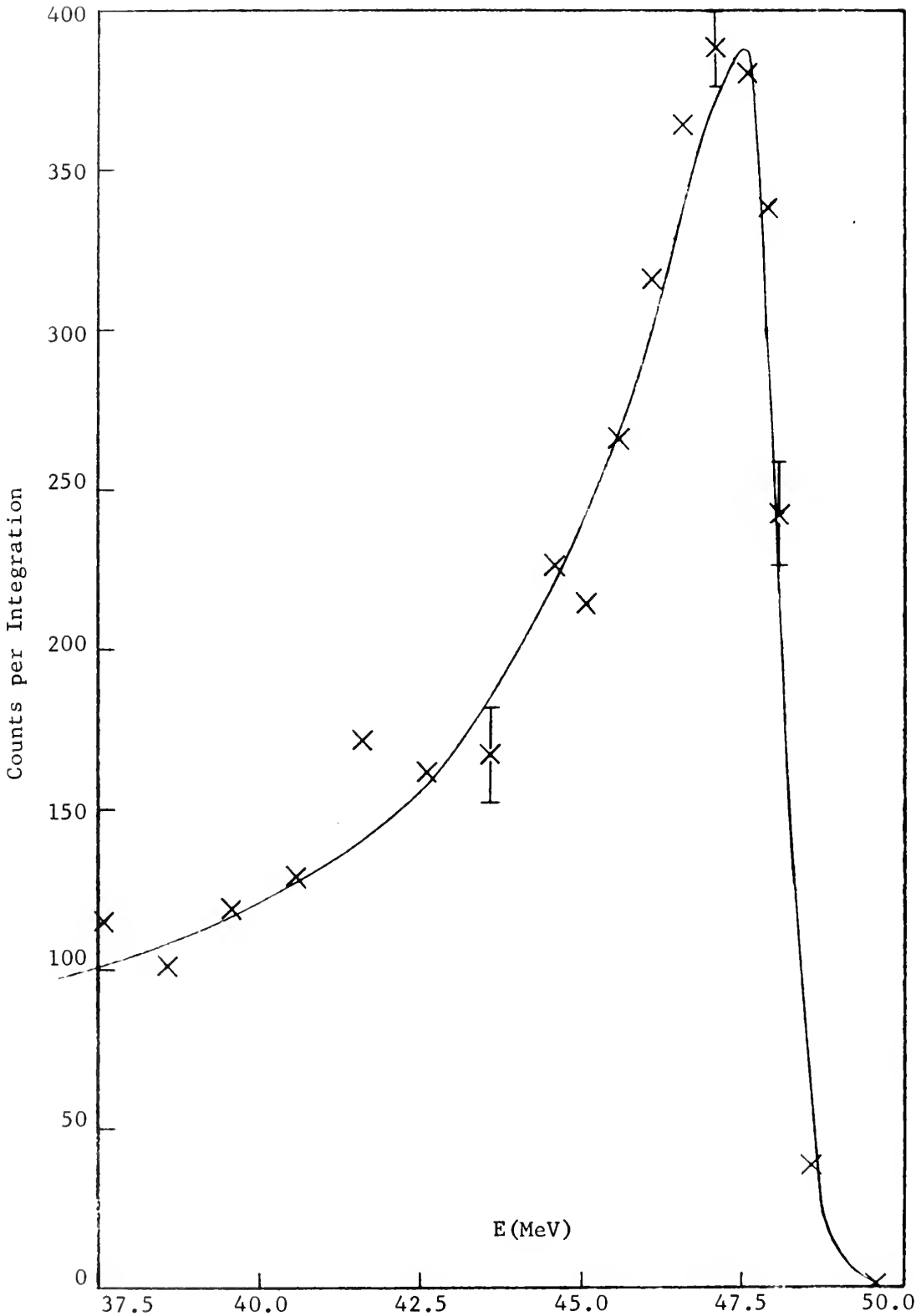

FIGURE 18. Cu, E_i = 53.63 MeV, t = 4.295 gm/cm^2

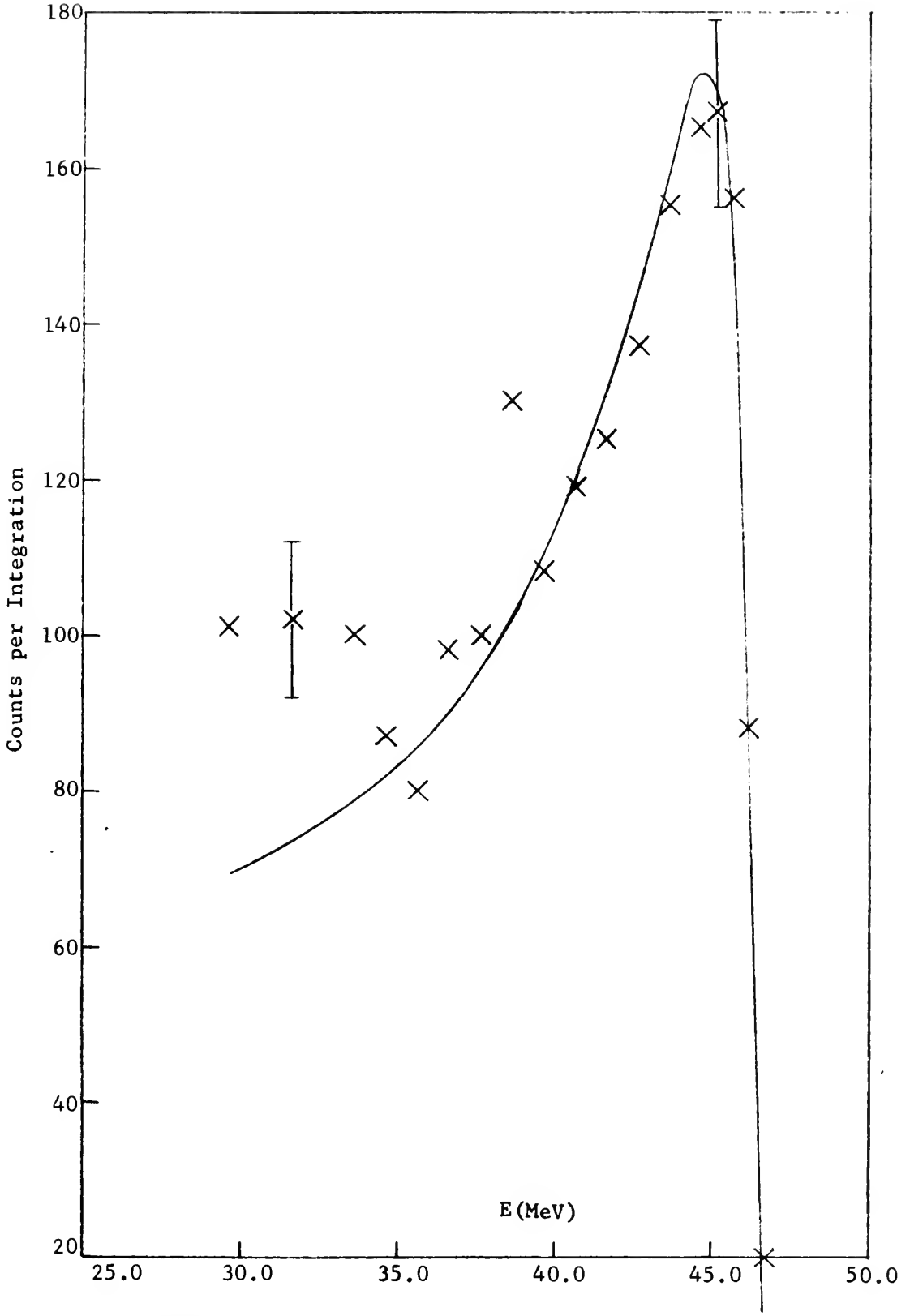

FIGURE 19. Cu, E_i = 53.63 MeV, t = 5.726 gm/cm^2

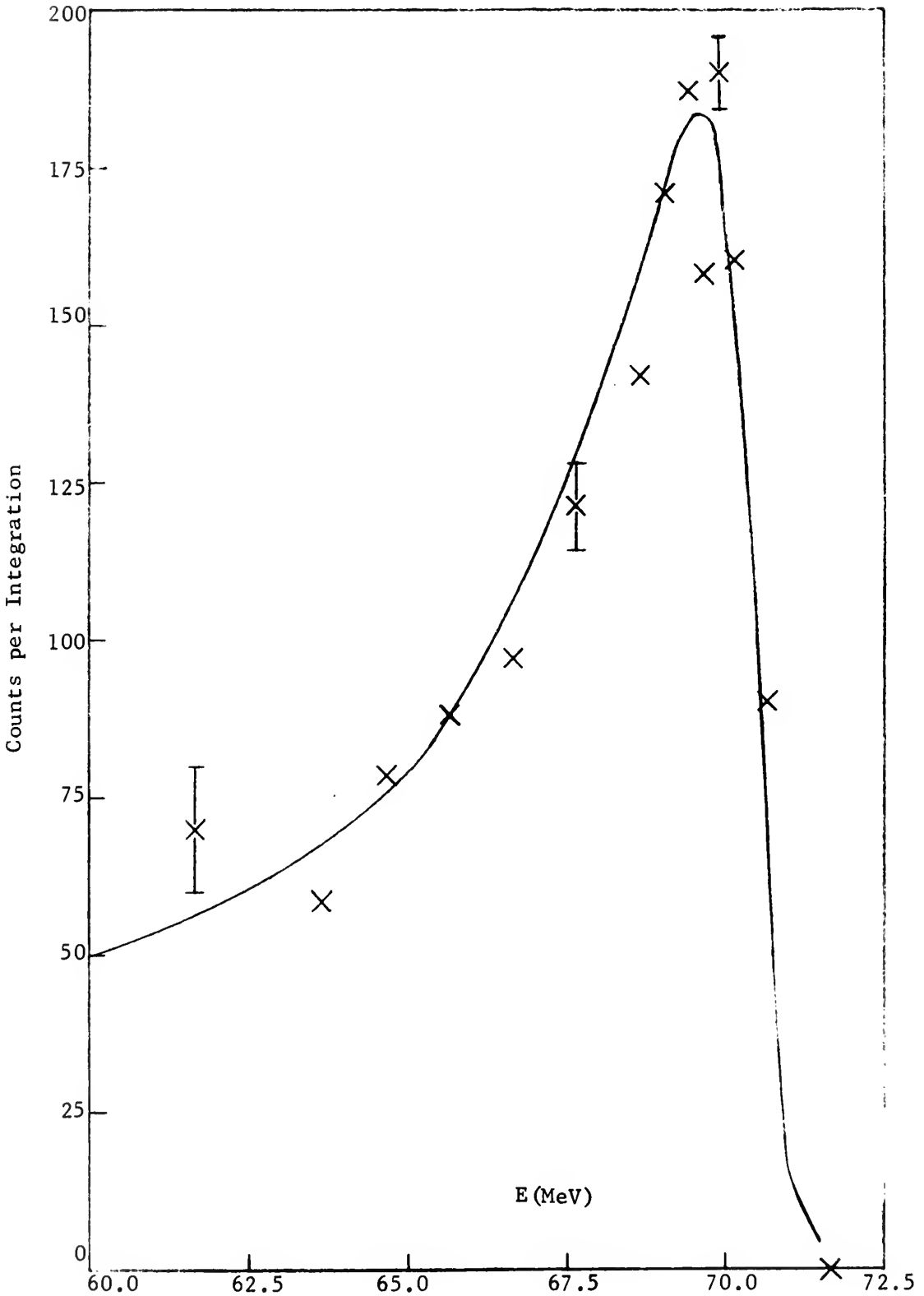

FIGURE 20. Cu, E_i = 76.02 MeV, t = 4.295 gm/cm^2

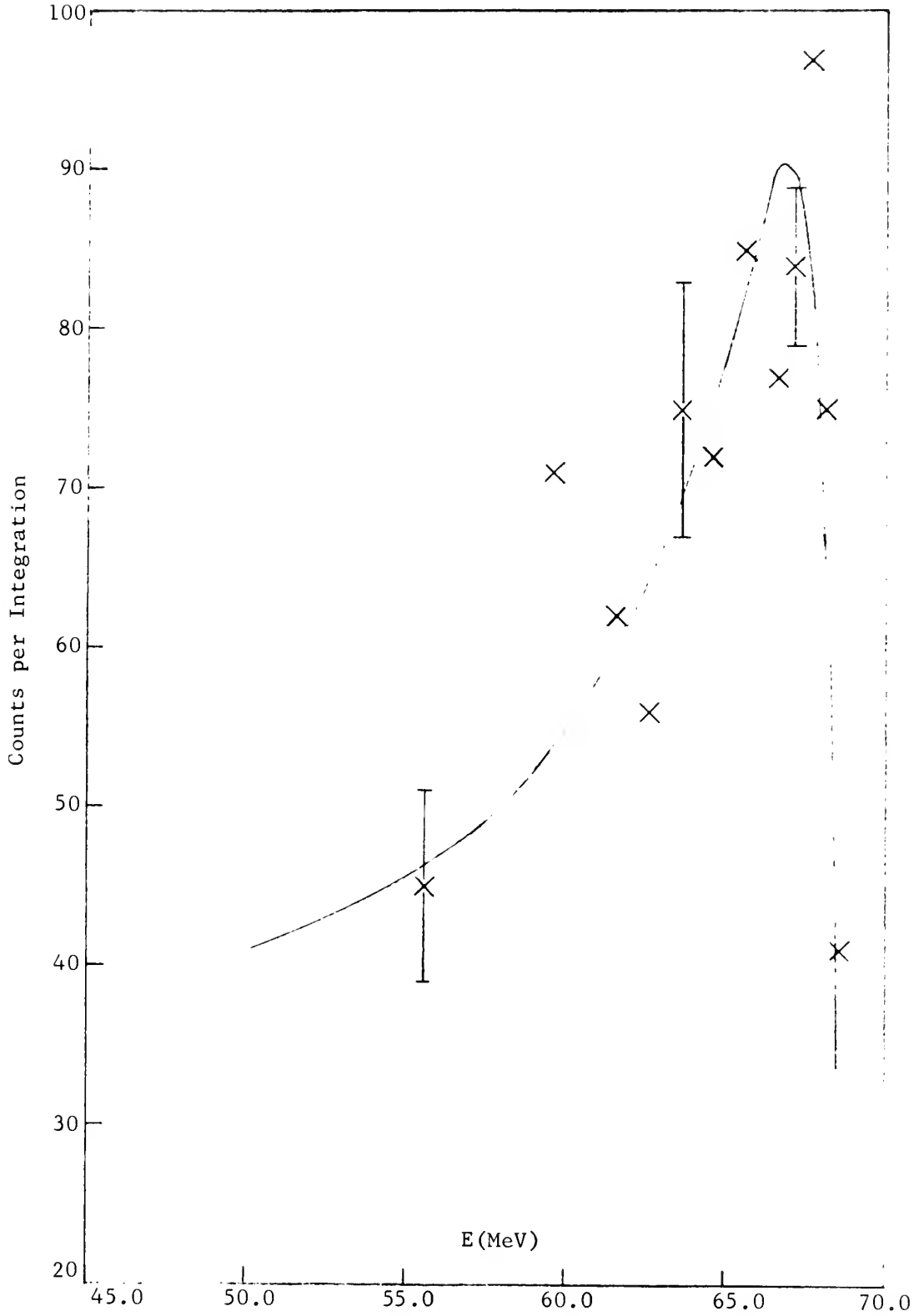

FIGURE 21. Cu, E_i = 76.02 MeV, t = 5.726 gm/cm^2

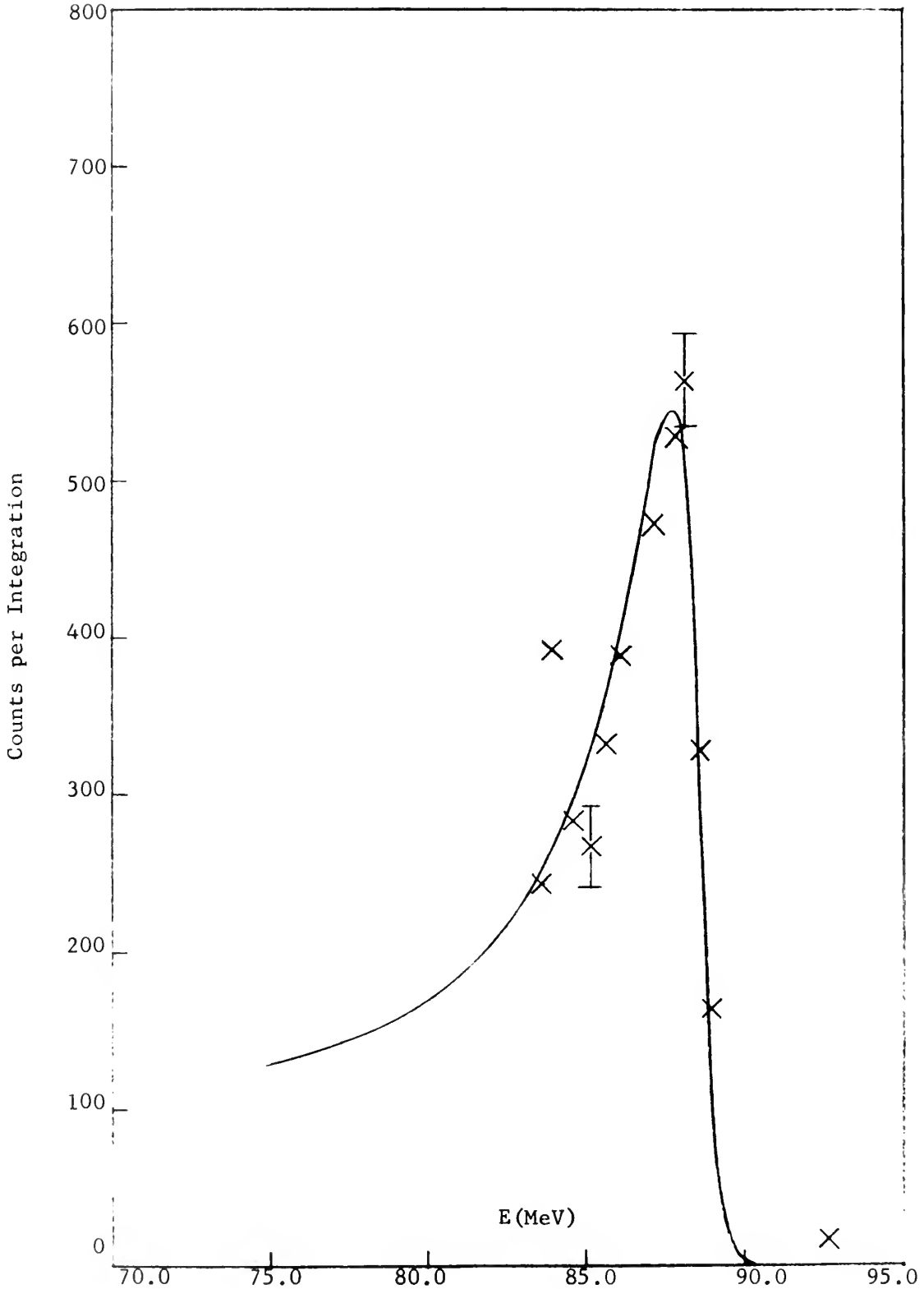

FIGURE 22. Cu, E_i = 9.407 MeV, t = 4.295 gm/cm^2

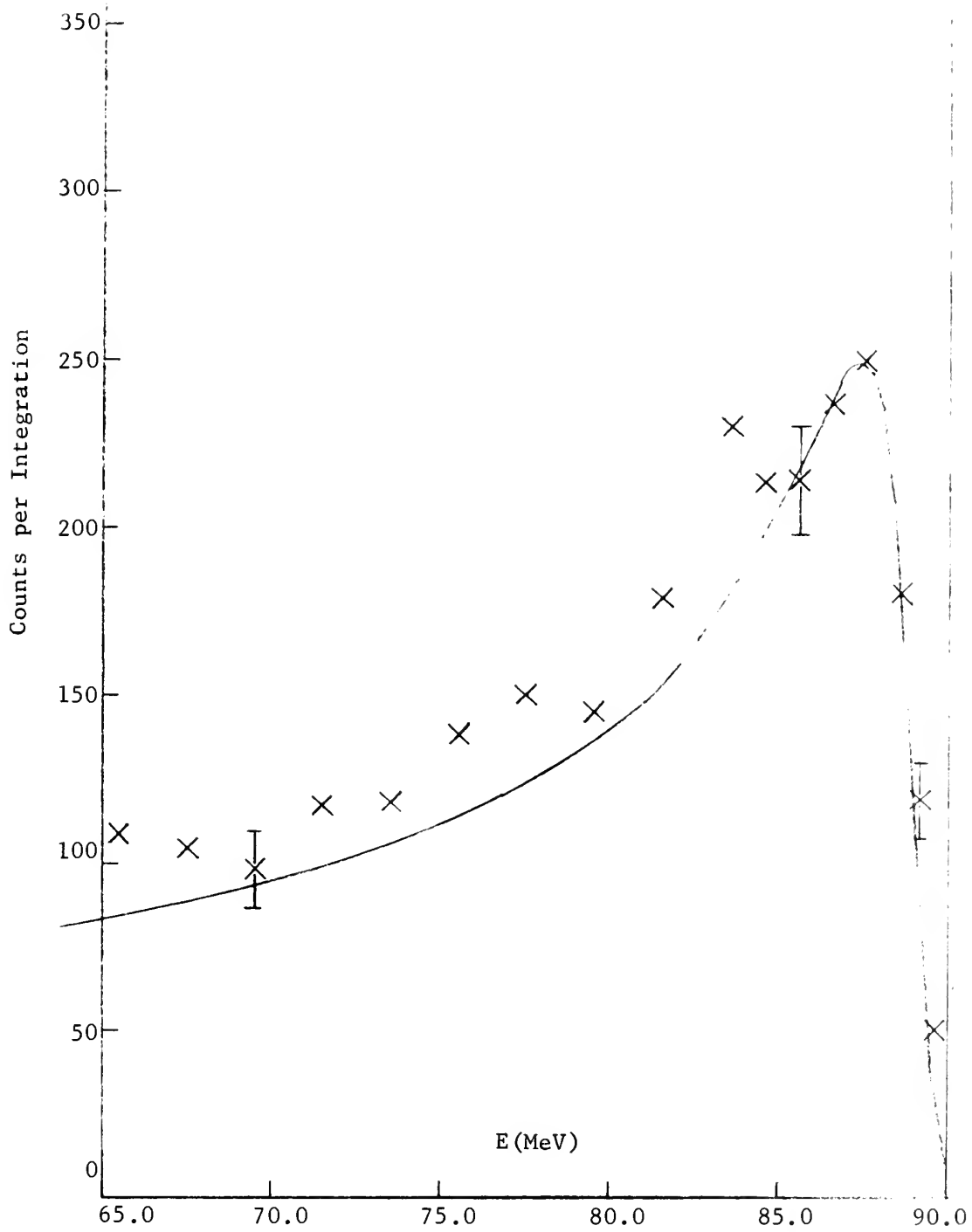

FIGURE 23. Cu, E_i = 96.66 MeV, t = 5.726 gm/cm^2

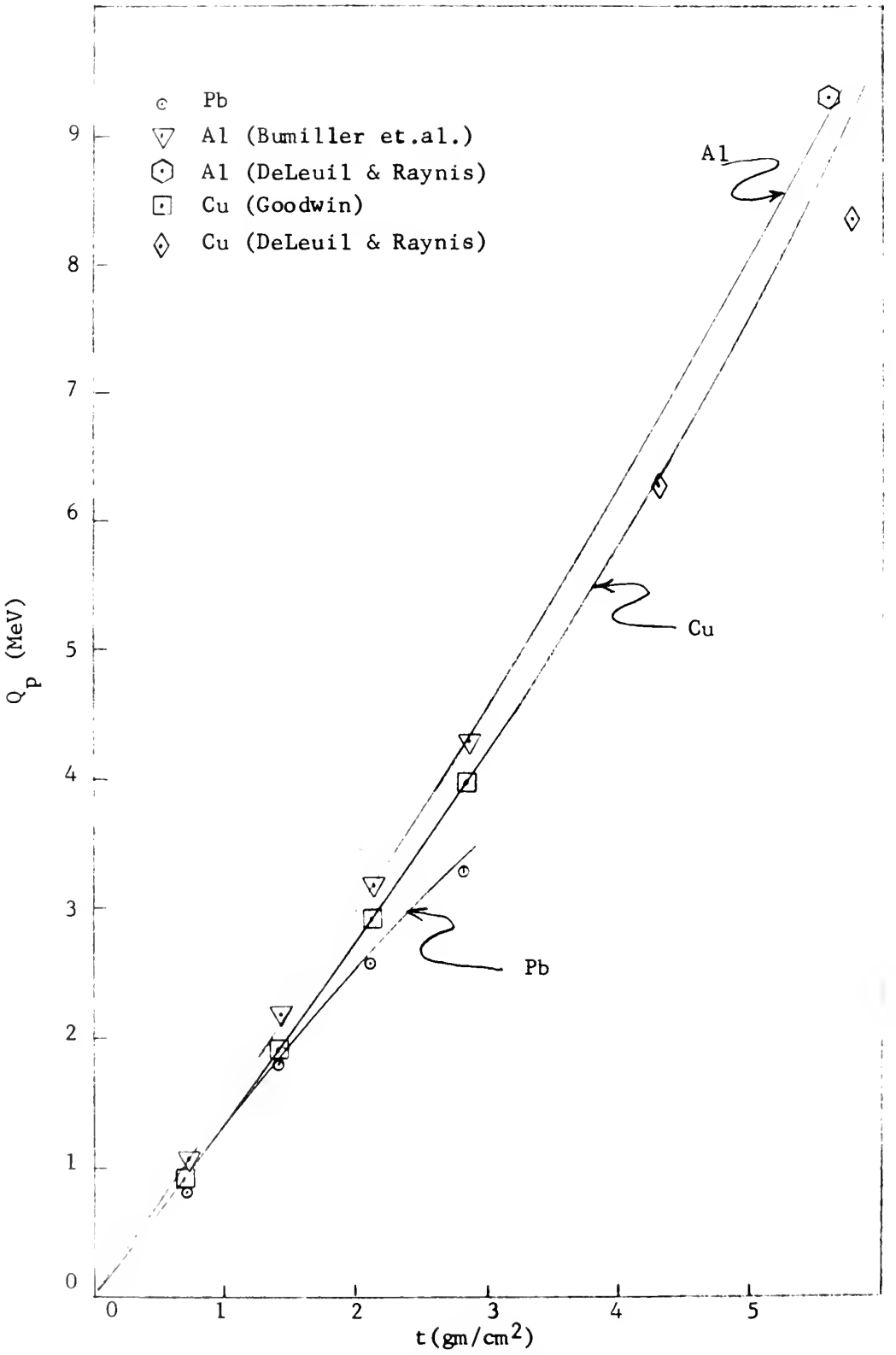

FIGURE 24. Most Probable Energy Loss at $E_i \approx 75$ MeV

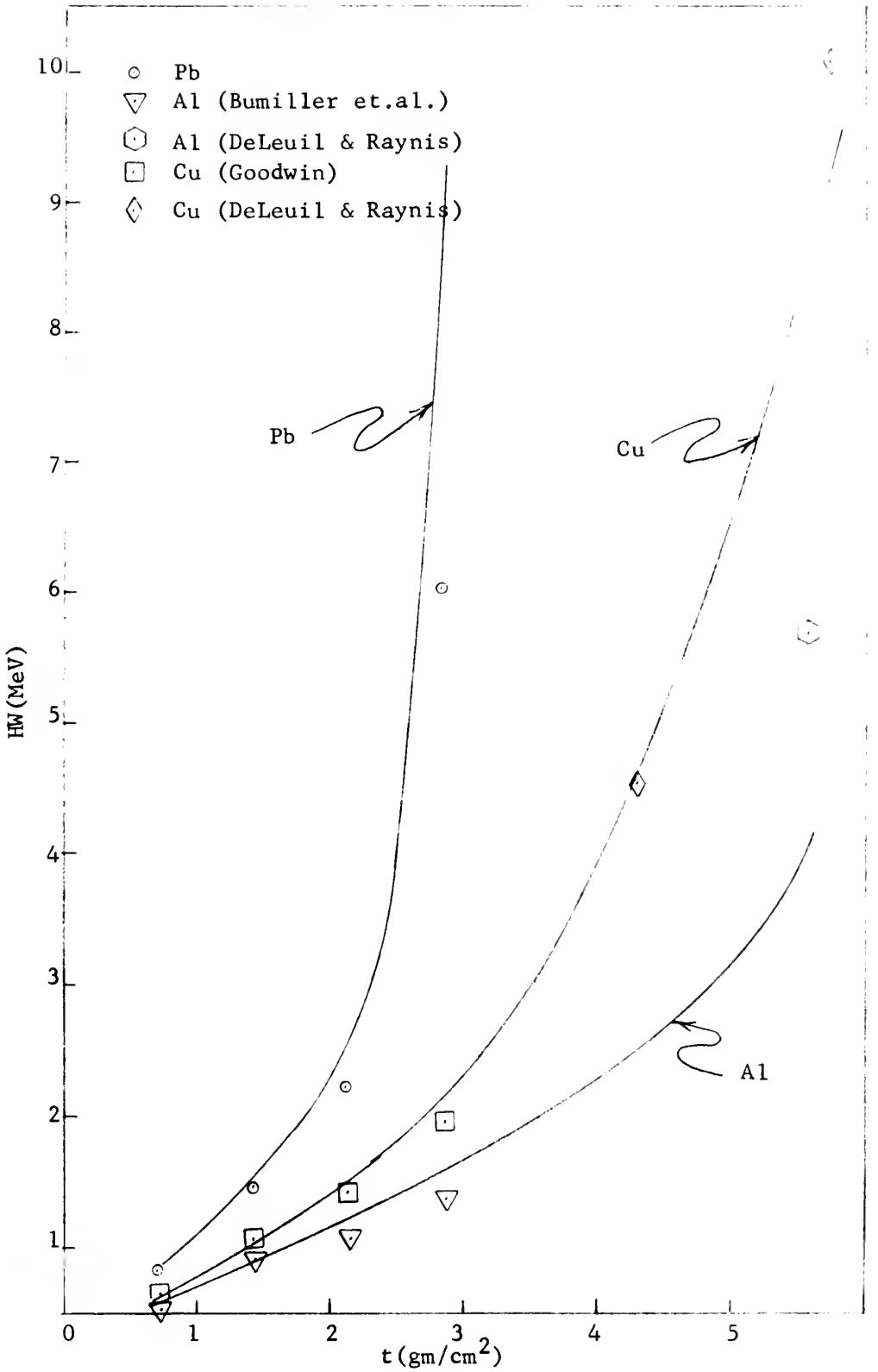

FIGURE 25. Half-Width at E_i = 75 MeV

```
      PROGRAM FOR COMPUTING ENERGY LOSS DISTRIBUTION

      IMPLICIT REAL*8 (A-H,L,Q-Z)
      DIMENSION E(100), C7(100), EX(200), CT(200)
      COMMON/$VL/EI,Q,QB,AR,Z,ALR,BETSQ
      EXTERNAL W
      WRITE (6,88)
   88 FORMAT ('1',11X,'EI',7X,'BETA**2',13X,'AR',11X,'ALPHA
     1 R',9X,'QBAR',12X,'QPI',////)

  READ N-NUMBER OF INPUT ENERGY BINS & M-NUMBER OF OUTPUT
  ENERGY VALUES

      READ (5,10) N,M
   10 FORMAT (2I10)
      READ (5,11) R
   11 FORMAT (F10.5)

  READ Z-ATOMIC NR, RHO-DENSITY, A-ATOMIC WT, & THE PARA-
  METERS OF THE MATERIAL FROM PAGE 514, STERNHEIMER PAPER

      READ (5,12) Z,RHO, A, AS, B, CS, SMALA, EM, X1
   12 FORMAT (6F10.4,/,3F10.4)

  READ ZERO PEAK ENERGIES AND COUNTS FROM HISTOGRAM

      READ (5,13) (E(J),C7(J),J=1,N)
   13 FORMAT (F10.2,F10.0)
      DO 100 I=1,M
  100 CT(I)=0.0

  EX(1) IS THE HIGHEST OUTPUT ENERGY VALUE DESIRED

      EX(1)=90.00

  DLTE IS THE SEPARATION BETWEEN ENERGY OUTPUT VALUES

      DLTE=.1

  COMPUTE ALPHA*R

      ALR=.0014*Z**2*RHO*R/A*(4./3.*DLOG(183./Z**(1./3.))
     1 +1./9.)
      T=RHO*R
      DO 200 J=1,N
      EI=E(J)

  COMPUTE BETA**2

      BETSQ=1.-.511**2/(EI+.511)**2

  COMPUTE A*R

      AR=.154*Z*RHO*R/(A*BETSQ)

  COMPUTE P/(M*C)

      X=DSQRT(EI**2+1.022*EI)/.511

  COMPUTE Q-BAR

      QB=AS*T/BETSQ*(B+.43+DLOG(EI)-BETSQ-CS-SMALA*(X1
     1 -DLOG10(X))**EM)

  COMPUTE Q PROBABLE IONIZATION

      QPI=AS*T/BETSQ*(B+1.06+DLOG(AS*T/BETSQ)-BETSQ-CS
     1 -SMALA*(X1-DLOG10(X))**EM)
      DO 300 I=1,M
      Q=EI-EX(I)
```

```
      EX(I+1)=EX(I)-DLTE
      IF(Q.LE.0.0) GO TO 300

  UPV ARE THE INTERMEDIATE LIMITS OF INTEGRATION

      U=.000001*Q
      V=.25*Q
      CALL DQG32(0.0,U,W,F1)
      CALL DQG32(U,V,W,F2)
      CALL DQG32(V,Q,W,F3)
      F=F1+F2+F3
      CT(I)=CT(I)+F*C7(J)
  300 CONTINUE
      WRITE (6,20) EI,BETSQ,AR,ALR,QB,QPI
   20 FORMAT (F15.2,F15.9,4F15.4,/)
  200 CONTINUE
      WRITE (6,77)
   77 FORMAT ('1',6X,'ENERGY',8X,'COUNTS',////)
      WRITE (6,21) (EX(I),CT(I), I=1,M)
   21 FORMAT (F11.2,F15.0)
      STOP
      END


       FUNCTION TO COMPUTE THE ENERGY LOSS DUE TO IONIZATION


      REAL FUNCTION WI*8(EI,Q,QB,AR,Z,BETSQ)
      IMPLICIT REAL*8 (A-H,L,Q-Z)

  STORE THE BLUNCK & LEISEGANG CONSTANTS

      REAL*8 S(4)/0.174,.058,.019,.007/,GAMMS(4)/1.8,2.0,3.0
     1,5.0/,LAMBDA(4)/0.0,3.0,6.5,11.0/

  STORE THE IONIZATION POTENTIALS AND ELECTRON LEVELS OF
  THE MATERIAL

      REAL*8 IM(6)/.08789,.01432,.00291,.00038,.000079,
     1 .000038/,NM(6)/2.,8.,18.,32.,18.,4./
      WION=0.0
      SB=0.0

   CALCULATE LAMBDA

      ALAM=(Q-QB)/AR+DLOG(EI/AR)-1.116

   CALCULATE B**2

      DO 100 I=1,6
      B=IM(I)*NM(I)*DLOG(2.*EI/(IM(I)*(1.-BETSQ)))
  100 SB=SB+B
      BS2=3.*SB/(7*AR)
      DO 400 K=1,4
      ER=((ALAM-LAMBDA(K))**2)/(GAMMS(K)**2+BS2)
      XW=DEXP(-ER)
      IF(XW.LE.1.0D-60)XW=0.0
      WIN=(S(K)*(GAMMS(K)/AR)/DSQRT(GAMMS(K)**2+BS2))*XW
  400 WION=WION+WIN
      WI=WION
      RETURN
      END


       FUNCTION TO COMPUTE THE ENERGY LOSS DUE TO RADIATION


      REAL FUNCTION WS*8(EI,X,ALR)
      IMPLICIT REAL*8 (A-H,L,Q-Z)
      WS = ALR/DGAMMA(ALR+1.)*(X/EI)**ALR/X
      RETURN
      END
```

```
 FUNCTION TO COMPUTE TOTAL ENERGY LOSS

REAL FUNCTION W*8(X)
IMPLICIT REAL*8 (A-H,L,Q-Z)
COMMON/&VL/EI,Q,QB,AR,Z,ALR,BETSQ
W=WI(EI,Q-X,QB,AR,Z,BETSQ)*WS(EI,X,ALR)
RETURN
END


SUBROUTINE DQG32(XL,XU,FCT,Y)

    PURPOSE
       TO COMPUTE INTEGRAL(FCT(X)

    USAGE
       CALL DQG32 (XL,XU,FCT,Y)
       PARAMETER FCT REQUIRES AN EXTERNAL STATEMENT

    DESCRIPTION OF PARAMETERS
       XL      - DOUBLE PRECISION LOWER BOUND
       XU      - DOUBLE PRECISION UPPER BOUND
       FCT     - FUNCTION TO BE INTEGRATED
       Y       - THE RESULTING DOUBLE PRECISION VALUE

    METHOD
       EVALUATION IS DONE BY 32-POINT GAUSS QUADRATURE

DOUBLE PRECISION XL,XU,Y,A,B,C,FCT
A=.5D0*(XU+XL)
B=XU-XL
C=.49863193092474078D0*B
Y=.35093050047350483D-2*(FCT(A+C)+FCT(A-C))
C=.49280575577263417D0*B
Y=Y+.81371973654528350-2*(FCT(A+C)+FCT(A-C))
C=.48238112779375322D0*B
Y=Y+.12696032654631030D-1*(FCT(A+C)+FCT(A-C))
C=.46745303796886984D0*B
Y=Y+.17136931456510717D-1*(FCT(A+C)+FCT(A-C))
C=.44816057788302606D0*B
Y=Y+.21417949011113340D-1*(FCT(A+C)+FCT(A-C))
C=.42468380686628499D0*B
Y=Y+.25499029631188088D-1*(FCT(A+C)+FCT(A-C))
C=.39724189798397120D0*B
Y=Y+.29342046739267774D-1*(FCT(A+C)+FCT(A-C))
C=.36609105937014484D0*B
Y=Y+.32911111388180923D-1*(FCT(A+C)+FCT(A-C))
C=.33152213346510760D0*B
Y=Y+.36172897054424253D-1*(FCT(A+C)+FCT(A-C))
C=.29385787862038116D0*B
Y=Y+.39096947893535153D-1*(FCT(A+C)+FCT(A-C))
C=.25344995446611470D0*B
Y=Y+.41655962113473378D-1*(FCT(A+C)+FCT(A-C))
C=.21067563806531767D0*B
Y=Y+.43826046502201906D-1*(FCT(A+C)+FCT(A-C))
C=.16593430114106382D0*B
Y=Y+.45586939347881942D-1*(FCT(A+C)+FCT(A-C))
C=.11964368112606854D0*B
Y=Y+.46922199540402283D-1*(FCT(A+C)+FCT(A-C))
C=.72235980791398250-1*B
Y=Y+.47819360039637430D-1*(FCT(A+C)+FCT(A-C))
C=.24153832843869158D-1*B
Y=B*(Y+.48270044257363900D-1*(FCT(A+C)+FCT(A-C)))
RETURN
END
```

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13. ABSTRACT

The energy distributions of electrons of about 54, 75, and 92 MeV were measured before and after passing through lead absorbers of thicknesses ranging from 0.706 to 2.825 gm/cm^2, and through copper and aluminum absorbers up to 5.726 gm/cm^2. The electrons were accelerated by the LINAC of the Naval Postgraduate School. A measurement to determine the optimum location of the absorber indicated that the separation between the scattering foil and absorber should not exceed 6 cm, if geometric difficulties are to be avoided. The most probable energy losses agree with the theory of Blunck and Westphal for all three materials and all thicknesses. The half-widths of the distributions agree with theory up to thicknesses of about 2 gm/cm^2. For greater thicknesses the experimental half-widths of copper absorbers appear to agree with theory; the experimental half-widths of aluminum are greater than theoretical predictions; and those of lead are smaller than theory predicts.

14 KEY WORDS	LINK A		LINK B		LINK C	
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High Energy Electrons						
Linear Accelerator (LINAC)						